United Kingdom Argo Project

Report on work 2001-2008

Notes: this report reflects the views of the UK Argo Expert Group and not those of Defra.

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Met Office

National Oceanography Centre, Southampton
UNIVERSITY OF SOUTHAMPTON AND NATURAL ENVIRONMENT RESEARCH COUNCIL

BODC British Oceanographic Data Centre

THE UNITED KINGDOM HYDROGRAPHIC OFFICE

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Introduction

Argo is an international activity with pilot programme status sponsored by the WMO and IOC and funded by national agencies. It aims to establish and then sustain a global array of 3,000 profiling floats measuring temperature and salinity to 2,000 m depth throughout the world's oceans. The programme was initiated in 2000 and in October 2007 reached its target of 3,000 operating floats throughout all the ice-free deep-ocean areas of the world, which are delivering around 100,000 observations each year. To achieve (and sustain) the 3,000 float array it will be necessary to deploy floats at a rate of approximately 800 per year.

Each float presently costs approximately £16K over a 4 year lifetime (including hardware, deployment and data management), and the annual cost of maintaining the 3,000 float array has been estimated to be ~US$20M [1]. From the outset it was recognised that Argo was too large for any nation to undertake individually and would require a co-ordinated international effort; this began in early 1999 with the initial meeting of the Argo Science Team (AST). In 2000 there were just 10 countries involved in deploying floats. Since then over 30 countries have deployed and operated floats or assisted with float deployments (Argentina, Australia, Brazil, Canada, Chile, China, Costa Rica, Denmark, Ecuador, France, Gabon, Germany, Iceland, India, Indonesia, Ireland, Japan, Korea, Kenya, Mauritius, Mexico, Mozambique, the Netherlands, New Zealand, Norway, Russia, South Africa, Spain, the UK and the USA, as well as the European Union and Pacific Island nations).

This report is an update of the UK Argo Expert Group report provided in summer 2006 and summarizes what UK Argo has achieved during the period from 2001 to end March 2008 and outlines our hopes and expectations for Argo.

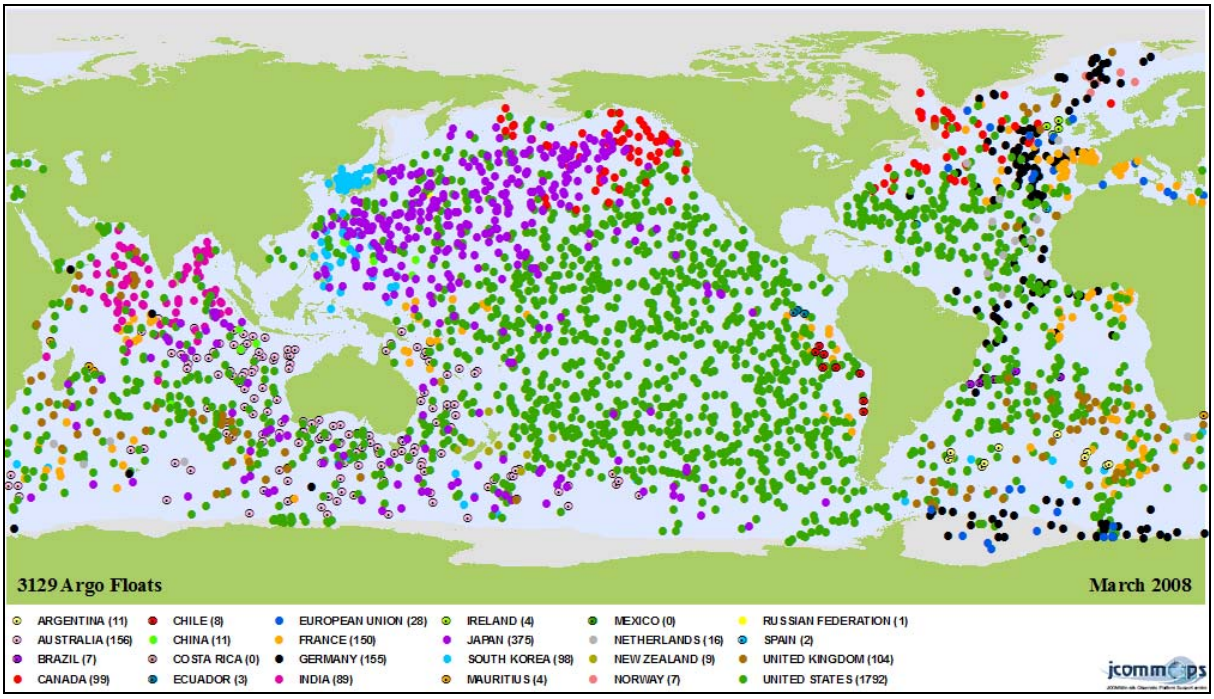

Figure 1. Showing the positions of Argo floats operating at end March 2008. Colours show each national contribution.

[1] S Wilson, 2001: Launching the Argo Armada. Presentation to JCOMM, 25 June 2001. WMO/TD-No. 1086.

Why Argo is needed

We are increasingly concerned about global change and its regional impacts. Sea level is rising at 3 mm/year and accelerating. Arctic sea ice cover is shrinking and high latitude areas are warming rapidly. Despite the inherent interannual variability that is observed within our climate, in a series of temperature observations dating back over 150 years, the warmest 10 years have all been since 1995. Extreme weather events cause loss of life and property. These effects are caused by a mixture of long-term climate change and natural variability. Their impacts are in some cases beneficial (lengthened growing seasons, opening of Arctic shipping routes) and in others adverse (increased coastal flooding, severe droughts, more extreme and frequent heat waves and weather events such as severe tropical cyclones).

Understanding (and eventually predicting) changes in both the atmosphere and ocean are needed to guide international actions, to optimize governments' policies and to shape industrial strategies. To make those predictions we need improved models of climate and of the entire earth system (including socio-economic factors). The lack of sustained observations of the atmosphere, oceans and land has hindered the development and validation of climate models. A recent analysis, which concluded that the currents transporting heat northwards in the Atlantic and influencing western European climate had weakened by 30% in the past decade, was based on just *five* research measurement campaigns spread over 40 years. How do we know whether this change was part of a trend that might lead to a major change in the Atlantic circulation, or due to natural variability that will reverse in the future, or is it an artifact of the limited observations? Argo will greatly improve the collection of observations from the ocean interior with increased sampling and better spatial and temporal coverage and help to answer such key questions.

Operational centres in Australia, France, Japan, the UK and the USA now routinely produce global and regional analyses of sub-surface properties using Argo data. These products will give early warning of significant temperature and salinity anomalies and changes in ocean circulation which can have longer-term impacts on weather patterns. For example, the North Atlantic Oscillation (NAO) is a phenomenon associated with winter fluctuations in temperature, rainfall and storminess over much of Europe. Observations indicate that there is a link between the NAO and North Atlantic SST.

Although it is generally not possible to predict individual weather events more than several days in advance, it is possible to provide useful information about conditions averaged over weeks to months and over large areas; e.g. the chance of above average winter rainfall over western Europe, or the likelihood of an El Niño event in the Pacific. Such long-range predictions (seasonal forecasts) depend on the existence of relatively slow changes in the upper ocean temperatures. The ocean-atmosphere link is particularly strong in the tropics (e.g. for El Niño), although useful predictions can also be made for mid-latitudes. For example, the 'cold winter' forecast for Europe for 2006/07 was produced using a combination of statistical models and complex climate models with interpretation by operational forecasters, where predictions were based on the sub-surface ocean temperature patterns.

Ocean information is required by many different organisations for various purposes; for disaster mitigation, ensuring safety at sea, marine and offshore operations, sustainable development and exploitation of the marine environment. Ocean forecasts are also used by the Royal Navy on a daily basis for a range of locations around the globe. The reliability of these forecasts has been shown to be significantly improved with the assimilation of Argo data. Government departments and agencies have increasing requirements for ocean information to protect and manage the marine environment in line with EC regulations. Although these requirements are primarily for coastal and shelf regions, predictions of conditions in the shelf seas rely on global data and models to provide boundary conditions. Subtle changes in physical ocean conditions such as sea temperature, currents or salinity have been shown to have profound effects on marine ecosystems.

UK Argo

The UK Argo programme is undertaken by a partnership which was developed following discussions between the NOAA Administrator and the Chief Scientific Advisor (CSA) in 1999. It has been funded by Defra, MoD and NERC and involves collaboration between the Met Office (who manage the programme), the National Oceanography Centre Southampton, the British Oceanographic Data Centre and the UK Hydrographic Office. The initial commitment made at a meeting called by CSA (Sir Robert May) in 1999 was that the UK would contribute to Argo, to at least a GNP level (presently 5.1%) of contribution at full deployment, with a clear expectation that Argo would need to be sustained in the longer term. It was agreed that funding for the UK Argo programme would initially be provided from research budgets within MoD, Defra (then DETR) and NERC, although funding was initial only agreed for the first 3 years (although funding extensions have subsequently been provided to March 2008). Despite considerable efforts it has not been possible to identify a longer-term funding line as there is presently no mechanism within UK Government to transition funding from research budgets to operational funding lines, hence it is likely that funding for the next few years will continue to be requested from existing research budgets.

The UK programme was initiated in 2000, with our first Argo floats being deployed in January 2001. To date 249 UK floats (including 5 donated to Mauritius) have been deployed in a number of different geographic areas, where deployments have focused on meeting specific UK requirements, while also contributing to the global array. The UK contribution is comparable to that from other developed countries and has provided a significant contribution to the growing Argo array. In particular UK Argo has taken a lead in deploying floats in sparsely populated regions (e.g. Arabian Sea, South Indian Ocean, South Atlantic and Southern Ocean) to demonstrate our commitment to establishing a genuinely global array. UK Argo has also been active within the international Argo Steering Team and the Argo Data Management Team.

UK aspirations for Argo

Our priority is to see the complete global 3,000 float array maintained for long enough for its full value to be demonstrated. The rationale for 3,000 floats is based on the scientific consensus to achieve an array with 3˚ × 3˚ resolution, which could be achieved with 3,000 evenly spaced floats. (However, in reality more than 3,000 floats would be needed to allow for non-uniform distribution and to deploy floats when opportunities permit into ageing parts of the array in advance of floats reaching the end of their life.)

We believe that 3˚ × 3˚ resolution is near optimal and cost efficient. Studies have been made by the Hadley Centre to estimate the resolution needed to monitor ocean heat content. These results are given in an unpublished paper by Matt Palmer and Helene Banks[2] in which HadCM3 output was sub-sampled at different resolutions. The results suggest that Argo should capture the variability and signal in ocean heat content and that 3˚ × 3˚ spacing is probably near optimal, as the temperature variability (noise) in the model decreased most rapidly when sampling up to 3˚ resolution, but the decrease was less (diminishing return)

[2] M Palmer and H Banks, 2002. Evaluation of ocean heat content in the HadCM3 couple ocean-atmosphere model compared with observations and the effect of sampling. Report for EC Gyroscope Project.

when sampled at higher resolution. A more recent Hadley Centre technical note[3] by Lesley Allison, using the 1/3˚ eddy-permitting HadCEM output, suggested that temperature variability decreased more rapidly for sampling up to 3˚ resolution, but the decrease was less when sampled at higher resolutions – again suggesting that 3˚ is probably about right.

For climate research the full value of Argo will only be realised when multi-year or decadal time-series are available and it is recognised that this could take as long as 10 years. Therefore, there is a need to maintain international support for Argo for at least this length of time, and the UK should advocate its commitment as long as there is the necessary international support for Argo.

An ongoing contribution of 50 floats per year would represent ~6% of the array, which we believe is not too large a contribution for UK to make given our strong international and maritime interests, and is consistent with the initial commitment made in 1999. Over the coming years, it will be necessary for international funding for Argo from partner nations to transition from being largely research-based to sustained (or operational) budgets. At the same time Argo will need to become fully integrated within the international (JCOMM) operational ocean observing systems.

Although the baseline Argo array should be focused on well-established technology, there remains an important role for the research community in improvement of the technology (e.g. operation under ice), development of new sensors (e.g. for biogeochemical measurements) and implementation of higher resolution regional arrays for scientific research.

Scientific results and application of Argo data

Within the UK we are already making full use of Argo data for ocean prediction, seasonal forecasting, climate research and hydrographic databases. Most of the improvements in capability already demonstrated (and discussed below) will be lost unless the array is maintained. A number of these results are outlined below and some are discussed in more detail in Annexes A to E, which are reproduced here largely as provided by the contributing authors in 2006. The importance of Argo as an essential underpinning capability for science was recognised in 2006 by the European Strategy Forum on Research Infrastructures (ESFRI) and Euro-Argo has been included within the ESFRI 'Roadmap' ftp://ftp.cordis.europa.eu/pub/esfri/docs/esfri-roadmap-report-26092006_en.pdf as one of 34 projects of wider European interest needing to be funded.

Ocean forecasting

Argo data (alongside other in-situ and remotely sensed ocean data) are assimilated into the operational Forecasting Ocean Assimilation Model (FOAM) system (see http://www.metoffice.gov.uk/research/ncof/foam/) run by the National Centre for Ocean Forecasting (NCOF) (see http://www.ncof.gov.uk). Assessments have demonstrated the positive impact of Argo data on FOAM predictions, giving a significant improvement in the accuracy of the analysis for the top 1,000m of the ocean. In particular the assimilation of co-located temperature and salinity significantly improves the salinity analysis. Argo data also enables the model to be validated, especially for salinity, and have also been used to improve and validate the mixed layer model used in FOAM. These results are discussed in more detail in Annex A.

[3] L Allison, 2004. Analysis of ocean heat content change in ENACT and study into the effect of data sampling resolution on an eddy-permitting ocean model (HadCEM). Hadley Centre technical note no. 58.

Seasonal forecasting

Seasonal forecasts (issued by the Met Office under the Public Weather Service) provide long-range warning of weather conditions, both for the UK (e.g. the 2005/06 cold winter, North Atlantic Oscillation) and where we have overseas interests (e.g. dependent territories and for the Armed Forces). They are also provided for developing countries (e.g. forecasts for drought conditions in the Sahel, East African rainfall). They are largely determined by statistical methods in which the forecast is based on precursor sea surface temperature patterns, as these change slowly and influence patterns in the weather. Argo enables us to observe the near-surface ocean temperature patterns that provide the basis for such seasonal forecasts.

A specific example of where Argo data had a direct impact on the UK forecast was in the North Atlantic in summer 2005 where monitoring of sub-surface temperature anomalies provided clear observational support for the statistical forecast of the forthcoming 2005/06 'cold winter' (see box).

Argo data and the 'cold winter' forecast for Europe for 2005/06

In September 2005 the Met Office issued a long-range forecast for the winter of 2005/06 of a '*two in three chance of a colder-than-average winter for much of Europe, and that if Europe were to experience below-average temperatures, parts of the UK - especially southern regions - would also be affected'.* There was also an indication for a drier-than-average winter over much of the UK.

The forecast was produced using a combination of statistical models and complex climate models with interpretation by operational forecasters. In particular Argo and other sub-surface data were used in examining temperature anomalies in the North Atlantic during 2005 in looking for the likelihood of re-emergence in the autumn of the spring anomaly pattern which would indicate a negative North Atlantic Oscillation mode during the 2005/06 winter. (A negative NAO is often associated with a colder and drier winter across northern Europe). The sub-surface data suggested that the spring anomaly pattern was indeed still present in the sub-surface and likely to re-emerge once autumn mixing eroded the near surface warm layer (see figure), and so provided further support for the long-range forecast issued in September.

This 'cold winter' forecast attracted significant interest in the UK with briefings to key Government departments, energy companies, health authorities, road and rail authorities, the media and the public. Preparing for cold weather can take several months and groups dealing with contingencies and long-term planning were able to use the forecast to best prepare for whatever the winter was to throw at them.

Following the 2005/06 winter it can be seen that Europe did experience below-average temperatures over a wide area through the winter 2005/6. The winter was very dry across the whole of the UK, warmer-than-average in the north, colder-than-average in the south. In the original forecast there were five main issues that have been verified and in four of these five cases, the predicted most likely event happened.

WINTER REVIEW		
	Prediction	**Outcome**
Mean temperature across Europe	Most likely colder than average	Colder than average for many areas
UK mean temperature	Most likely colder than average	Warmer than average
Southern UK mean temperature	Most likely colder than average	Colder than average
UK precipitation	Most likely drier than average	Drier than average
North Atlantic Oscillation (NAO) for the winter season	Negative	Negative

Table 1. Verification of winter forecast for 2005/06.

Without information from Argo on the structure of the sub-surface temperature anomalies it is unlikely that such a clear forecast could have been made on this occasion. However, it should be borne in mind that not all winters will have a strong signal one way or the other or the other, and in these cases it will always be difficult to provide definitive forecasts.

Numerical models are also run to make seasonal forecasts. Although initialising numerical seasonal forecasting models with Argo data improves the accuracy of their predictions of surface temperature, the models are not presently any more accurate than the statistical techniques as they are still experimental and not yet capable of exploiting the full benefits from the Argo data; this is an area of continuing research and development.

The Met Office's seasonal forecast system produces a forecast out to six-months ahead once a month using the GLOSEA (Global Seasonal) coupled atmosphere-ocean general circulation model. Initial conditions are provided by an ocean analysis. Data-withholding experiments have been carried out for the period 2000-2004 and show the benefits of the Argo data on the system. Although the 5 year retrospective period is short in terms of accounting for the variability in forecast skill, a more general assessment of predictability of ocean heat content shows a positive benefit for all lead times and forecast seasons from forecasts initialised using Argo data. In particular, the global coverage of Argo data acts to remove biases in the analysis resulting from XBT data and the ocean model/atmospheric forcing. Annex B gives more details on this work.

For further information about seasonal forecasting at the Met Office see http://www.metoffice.gov.uk/research/seasonal/.

Climate monitoring and prediction

The oceans provide the largest reservoir of heat within the Earth's climate system. Since 1955 it is estimated that the global ocean has absorbed over 90% of the heat absorbed by the climate system. However traditional observing methods have led to considerable uncertainty in the estimates of ocean heat content. Climate models suggest that ocean heat absorption will be the largest source of sea level rise over the coming century. Argo will monitor the main heat sink of the climate system and the main source of sea level rise.

A key aspect of climate monitoring is to distinguish natural variability from long-term trends. Global observing systems have several advantages for this. Natural variations in the global climate are smaller than in most regional climates. This makes the detection of long-term global trends easier than that of long-term regional trends. The geographical patterns of changes observed by global monitoring systems can be compared with the patterns (fingerprints) of changes simulated by Earth System climate models in response to greenhouse forcing and the patterns of natural variability within climate models. In this way observed changes can be attributed to anthropogenic causes. In summary, global monitoring systems can detect climate changes with greater certainty and more quickly than regional monitoring systems and can be used as a firm foundation for interpretation of regional monitoring results. Without global Argo coverage we cannot quantify the role of the oceans in climate change.

Historical observations of sub-surface temperature and, particularly, salinity are extremely sparse and have in the past been limited to a small number of repeat hydrographic transects. Argo has revolutionised our ability to observe the sub-surface and enabled us to make the most globally complete estimates of heat and freshwater content and sea-level to date, and to resolve ocean variability on monthly timescales. Without resolving ocean variability it is difficult, if not impossible, to reliably determine signals of climate change. Large, previously unsampled, areas of the ocean (particularly in the Southern Hemisphere) are now monitored

by Argo which fills previous enormous gaps in our observation of ocean heat and freshwater content.

The increased spatial and temporal resolution of temperature and salinity data from Argo are already helping to understand better the variability of the climate system, as demonstrated by results from UK floats deployed in the South Indian Ocean (a region where changes in salinity are believed to be a fingerprint of anthropogenic climate change). In particular these floats have shown that there are basin-scale changes on timescales longer than annual but shorter than decades, where the magnitude of salinity changes is sufficiently large that Argo can detect them.

Modelling studies at the Met Office Hadley Centre have shown that the traditional approach of occasional (and generally haphazard) observation of the sub-surface ocean through research cruises does not produce sufficiently close sampling of the ocean (in space or time) to allow rapid detection of the effects of climate change. Argo is the only observing system that provides the global coverage and frequency of sampling required.

Argo data is also a key element in decadal climate prediction. It has been demonstrated by Smith et al, 2007 [4] that initialisation of ocean heat content is a key element adding skill to decadal predictions of regional climate. Figure 2 shows how Argo data significantly influences predictions of the Atlantic thermohaline circulation (THC).

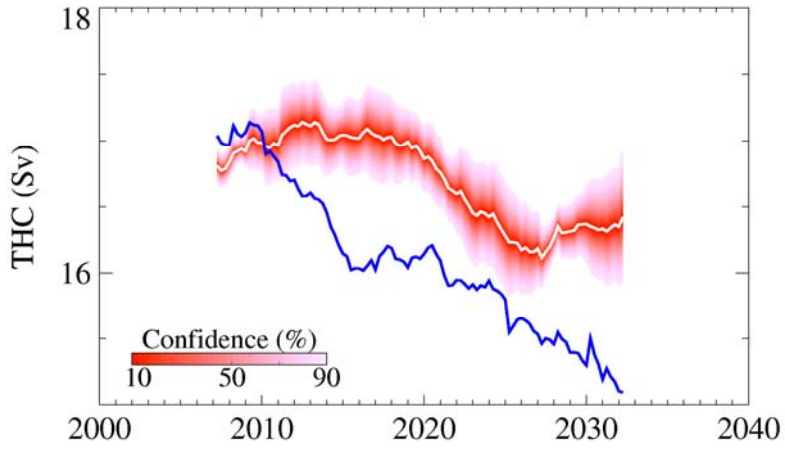

Figure 2. Time series of 5-year running mean thermohaline circulation predicted from March 2007 with (white curve) and without (blue curve) ocean initialisation (primarily using Argo data). Uncertainties in the ensemble mean are indicated by the red shading.

The THC is responsible for the relatively mild climate of western Europe and is expected to weaken as a result of global warming, hence accurate prediction of the THC is a key to predicting regional patterns of surface temperature and precipitation for the coming 10-100 years. Reliable climate forecasts on these time scales are needed to guide government policies on mitigation and adaptation. The THC is currently being monitored by the NERC RAPID programme. This monitoring has recently been committed by NERC until 2014. Model studies have shown that if the THC measurements are combined with observations from elsewhere in the Atlantic (as would be provided by Argo), long term trends in the THC can be more quickly distinguished from year-to-year variations. This combination of observation types will better allow us to monitor how fast the THC is changing, and to reduce uncertainty in THC predictions. It may eventually be possible to monitor the THC without the

[4] Smith, D. M., S. Cusack, A. W. Colman, C. K. Folland, G. R. Harris and J. M. Murphy, 2007, Improved surface temperature prediction for the coming decade from a global climate model, *Science*, 317, 796-799, doi:10.1126/science.1139540.

need for continuous maintenance of the RAPID array by applying Argo data with altimeter data in ocean models. This hypothesis can only be tested by running the Argo and RAPID systems in parallel for at least a decade.

The governments second Charting Progress report, see http://www.defra.gov.uk/environment/water/marine/uk/stateofsea/, will provide an updated assessment of the state of the seas around the UK. Argo will provide a key data set for characterising the state of the Atlantic and any change and variability in its climate. This information is needed as changes in the North Atlantic directly affect UK seas and are needed to place observed changes in UK waters into proper context. Failure to provide such contextual information could lead to incorrect interpretation of data from UK waters and policies being based on incomplete information.

However the full value of Argo for climate science will only be realised when multi-year or decadal time-series are available which could take at least 10 years. The HadGOA, global sub-surface ocean analysis of temperature and salinity, dataset is being developed in the Hadley Centre to support climate model evaluation and climate monitoring. The accuracy of this dataset will be significantly enhanced by the continued availability of Argo data.

Annex C, originally prepared in 2006, gives further information on work carried out on the application of Argo data for climate.

Ocean science

The advantages of the free and unrestricted data policy for Argo have already been seen in that Argo data are being used by scientific researchers outside of the 'Argo community'. From 2001 to date more than 450 scientific papers have drawn on measurements from Argo. Wider use of the data for scientific and educational purposes should continue to be encouraged.

Argo data are being used by various researchers in the UK for improving understanding of ocean properties (e.g. heat storage and budget, ocean circulation and mixing) as well as how they may be better exploited in ocean models (e.g. improved salinity assimilation) for ocean prediction and seasonal forecasting. The UK Argo Users Group was established in 2004 to bring together the wider 'user' community in the UK of those working with float data and on the technology. Since then several meetings of this group have been held during which a wide range of research work has been presented. These meetings have demonstrated the increasing number of scientists in the UK from various institutes, and not necessarily those associated with the UK Argo programme, who are using Argo data. This is largely a consequence of the open data policy adopted by Argo. Examples of such work (from 2006) are presented in Annex D (North Atlantic ocean heat content and water mass properties) and Annex E (ocean circulation).

A more recent example of new results from the School of Environmental Sciences, University of East Anglia, Norwich, (Matthews et al, 2007),[5] is the use of Argo, with its unprecedented space-time coverage of the upper 2000 meters of the global ocean, to provide definitive evidence of a deep tropical ocean component of the Madden-Julian Oscillation (MJO). The amplitude of the deep ocean anomalies is up to six times the amplitude of the observed annual cycle. This deep ocean sink of energy input from the wind is potentially important for understanding phenomena such as El Niño–Southern Oscillation and for interpreting deep ocean measurements made from ships.

[5] Adrian J. Matthews, Patama Singhruck and Karen J. Heywood (2007). Deep Ocean Impact of a Madden-Julian Oscillation Observed by Argo Floats. Science 318, 1765.

UK floats deployed

As noted earlier our first UK floats were deployed in January 2001, with 249 floats having been deployed by to date. Table 2 shows the numbers of floats deployed each (calendar) year and the locations of deployments are shown in Figure 3.

Our floats have been deployed in a wide variety of ways: from both UK and overseas research ships, by the RN, from VOS ships (in the latter two cases by regular crew) and from the air (by the US Navy). As can be seen from Figure 3 the majority of UK floats have been deployed in the Southern Hemisphere with the aim of building the global array. Other countries (notably France, Germany, Canada and US) have committed sufficient floats to the North Atlantic which was one of the first regions to be well-populated, hence the relatively low number of UK floats deployed in that region. Indeed the UK programme was among the first to put floats in the South Atlantic/Southern Ocean, Arabian Sea and South Indian Ocean. Of the 249 floats deployed 25 have been MARTEC Provors while the rest have been Webb Apex.

Year	UK Argo floats	Argo equivalent floats	Floats donated to Mauritius
2001	27	2	
2002	34	4	
2003	22	15	1
2004	45		2
2005	28		
2006	24		2
2007	31	2	
2008 (estimated)	35		

Table 2. Numbers of UK floats contributing to Argo deployed by year. Argo equivalent floats are those that have been procured by research grants as opposed to regular Argo funding.

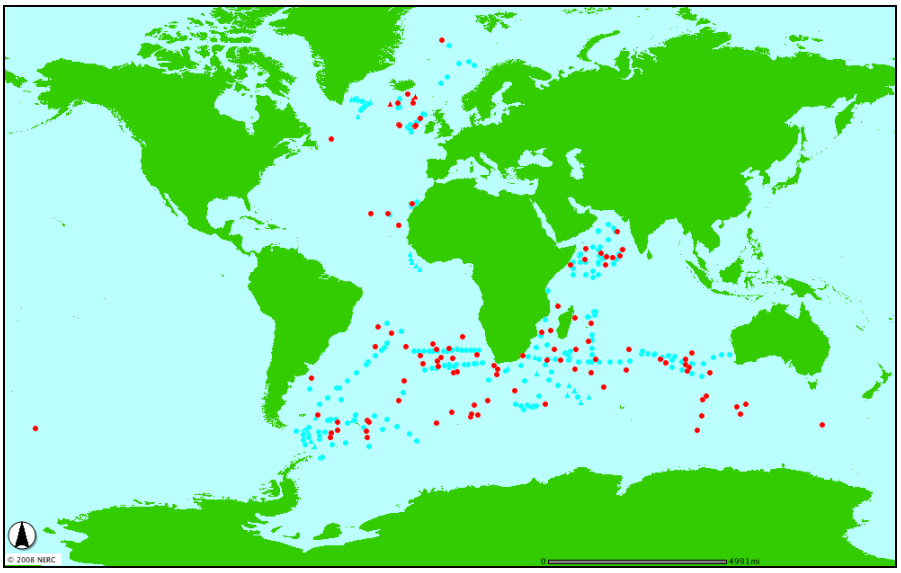

Figure 3. Present distribution of operating (•) UK floats and locations of float deployments (•).

Figure 4. Showing various deployment techniques, left, float being deployed using ropes from HMS Endurance; centre, night-time VOS (free-fall) deployment using a deployment slide from Glasgow Maersk and right, US Navy air deployment (photograph courtesy of Webb Research).

Figure 5 shows the numbers of UK floats deployed alongside the number of floats presently operating (i.e. reporting profiles). It can be seen that the number of operating floats is currently around 100.

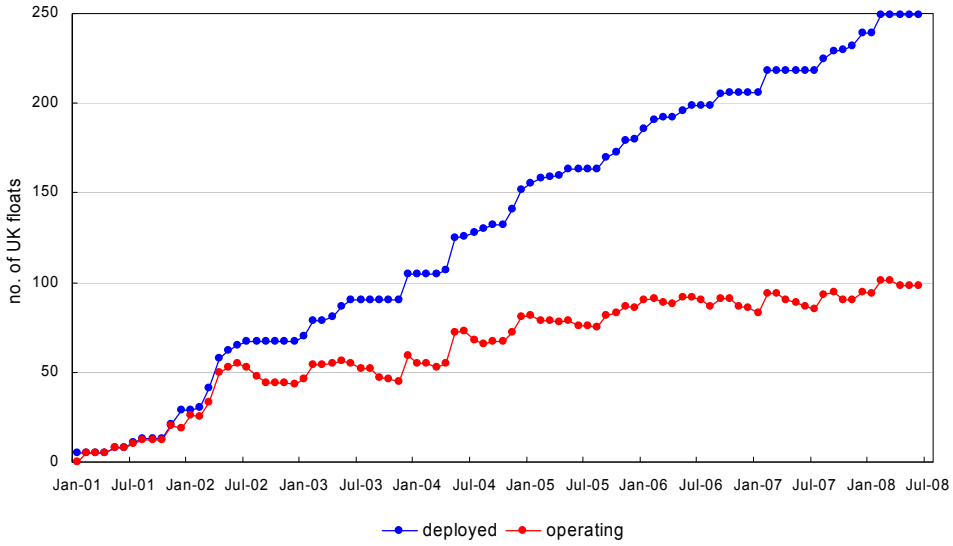

Figure 5. Number of UK floats deployed (blue) and operating (red) since the start of 2001.

Float reliability

Demands from the Argo community have led to various technical improvements in float technology to improve reliability. This is an ongoing process, and identification of problems is difficult since very few floats are recovered. However, a number of technical problems with floats have been discovered and addressed. In particular UK Argo experienced a number of early float failures in 2002 and 2003 due to the motor backspin and pressure transducer problems (discussed in more detail in Annex F), as can be seen in the dips in the number of operating floats (Figure 5, red curve) in the summers of 2002 and 2003. However, these failure modes have been addressed and other modifications (bladder cowling apertures closed to prevent sediment ingress, ice avoidance algorithms) have been developed to further reduce the number of premature failures.

As a result estimation of float failure rates and lifetimes is complicated, since the design has changed as each modification has been made. Nevertheless, there is clear evidence that the rate of early float failures has been greatly reduced, see Figures 6 and 7 for Apex floats and Figures 8 and 9 for Provor floats. Virtually all UK floats included in these figures have a

2,000 m profile depth on each cycle, although a small number of floats deployed in early 2006 were set to only profile deep every 4th cycle. However, the UK Argo Expert Group since recommended that UK floats should profile to 2,000 m on every cycle as far as possible.

Apex floats

Figure 6 (over) for Webb Apex floats, clearly shows the relatively high number of early failures for floats deployed in 2002 (motor backspin) and 2003 (pressure transducer), with a significant reduction in early failures for floats deployed in 2004 and 2005. Here the number of cycles (which may be greater than the number of profiles reported) has been normalised (reduced) for floats that only profile deep intermittently. Also invalid cycles (e.g. made by floats when the pressure transducer has failed) are omitted.

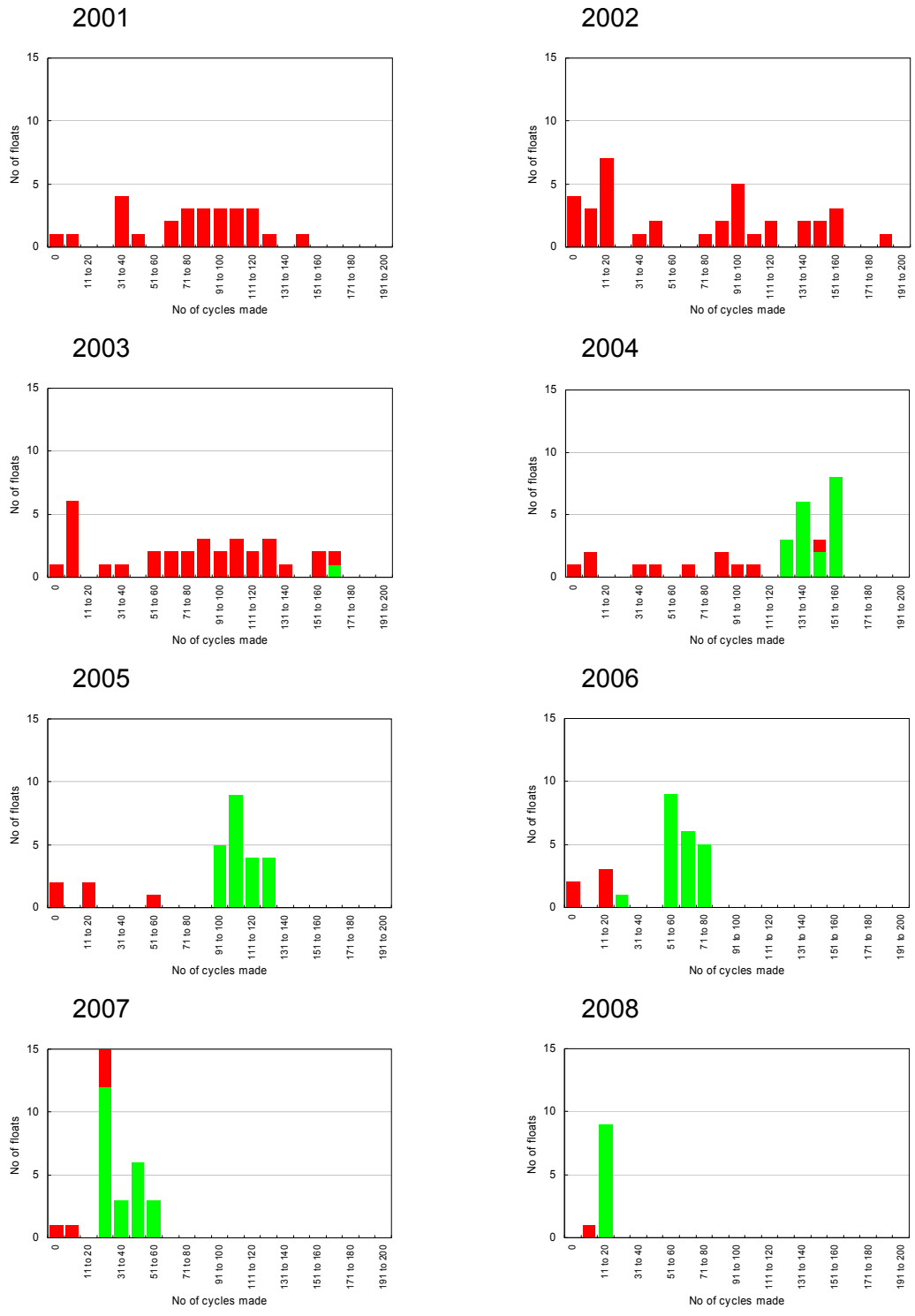

Figure 6. Showing the numbers of cycles completed for active (green) and dead (red) Apex floats grouped against year of deployment (as at end June 2008). Figures exclude floats where deployment failure has been confirmed.

The figures for 2001 to 2003 suggest that the typical float lifetime (excluding early failures) is between 70 to 120 profiles, with an average lifetime expectation of around 100 profiles, although a few floats have survived for over 4 years. This is consistent with the findings of CSIRO Marine who suggested in 2004 that the nominal battery lifetime was for around 100 profiles (to 2,000m). A further design change, the bypass diode modification to mitigate 'battery flu' (see Annex F) was implemented in February 2004. Figure 7 shows there has been a distinct improvement in the survival of our floats deployed from 2004 to those

deployed in earlier years. Only 30 to 40% of floats deployed before 2004 made more than 100 profiles, although our longest-living float (from 2002) reached 185 profiles before expiring. However for floats deployed in 2004 over 70% reached the 100 profile mark. The reduction in early failures is also seen in floats deployed in 2005. For the 2006 floats we believe that 3 of the early failures (plus 2 in 2007) were due to ice damage rather than float failure, to avoid this we now specify ice-avoidance algorithms on any floats to be deployed in regions where ice might be encountered.

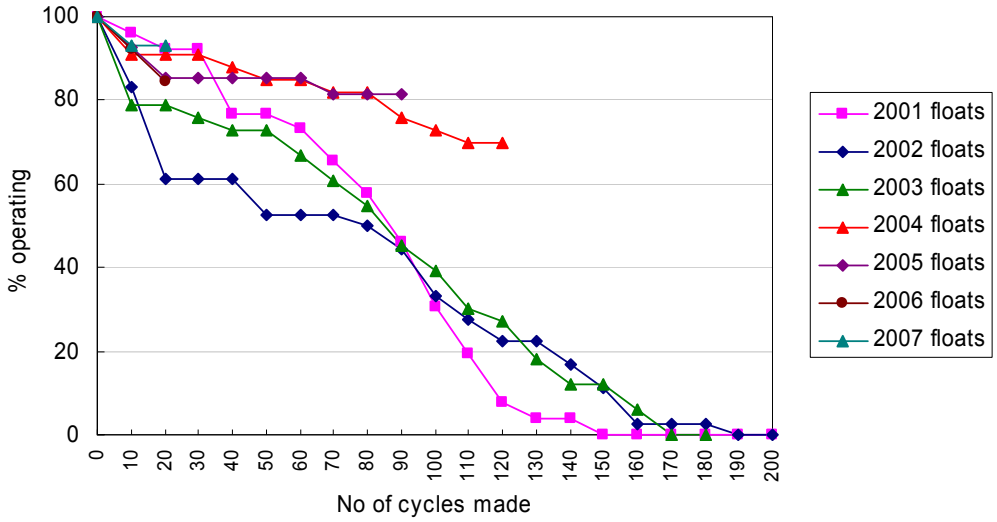

Figure 7. Showing the % numbers of Apex floats, deployed by year, operating. Statistics exclude floats where deployment failure has been confirmed and the number of cycles is adjusted for those floats that have shallower profiles or only profile deep intermittently.

The use of lithium batteries can provide greater energy with an expected increase in float lifetime. However at present the main float manufacturer (Webb Research) is unwilling to provide floats with lithiums due to the increased hazard (and potential liability issue) with them and so the batteries have to be changed prior to deployment. So far 16 UK floats deployed in 2007 and 2008 have had lithium batteries installed, however as these floats are still relatively young it is too early to quantify the effect on lifetime. At a cost of ~£500 per float this should be a very cost effective modification, since it ought to increase the float lifetime by ~1 year.

Provor floats

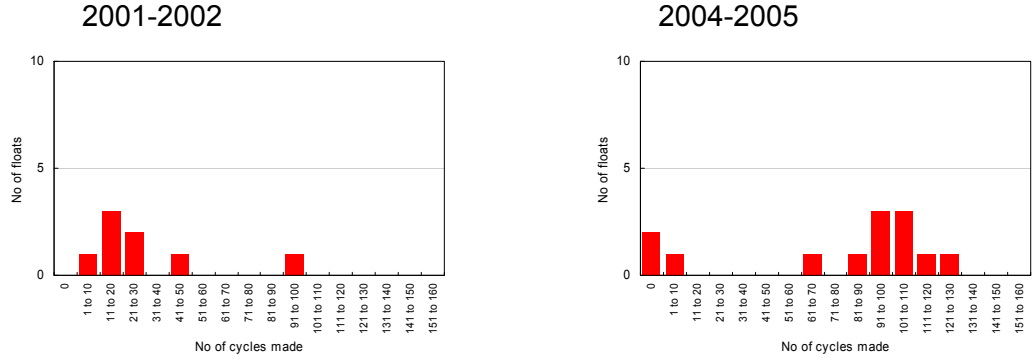

Figure 8. Showing the numbers of cycles completed for active (green) and dead (red) Provor floats grouped against years deployment (as at end June 2006). Figures exclude floats where deployment failure has been confirmed.

Figure 8 shows figures for the MARTEC Provor floats. As fewer of these have been deployed the figures are grouped for floats deployed from 2001 to 2003 (8 floats) and 2004 to 2005 (13 floats). The early Provors (2001, 2002) suffered from a problem in which the salinity exhibited a major jump and offset. These floats all used FSI (inductive) salinity sensors, whereas all our Apex floats have SeaBird sensors. Explanations were movement of the flotation collar and problems due to contamination by the anti-foulant. Of the 8 floats deployed in 2001 to 2003 only one float did not fail early (making 93 cycles) although the salinity sensor failed much earlier. The Provors deployed in late 2004/early 2005 had the anti-fouling coating removed and their survivability shows a distinct improvement over those deployed in 2001 and 2002 (see Figure 9). However, most of these floats have failed after around 100 cycles, with the longest surviving for 122 cycles. Of the 4 Provors (all upgraded by Martec) deployed in 2007, one failed after 4 cycles the others are approaching 35 cycles. Although Provor floats are fitted with lithium batteries as standard, our Provors have not been seen to operate for longer.

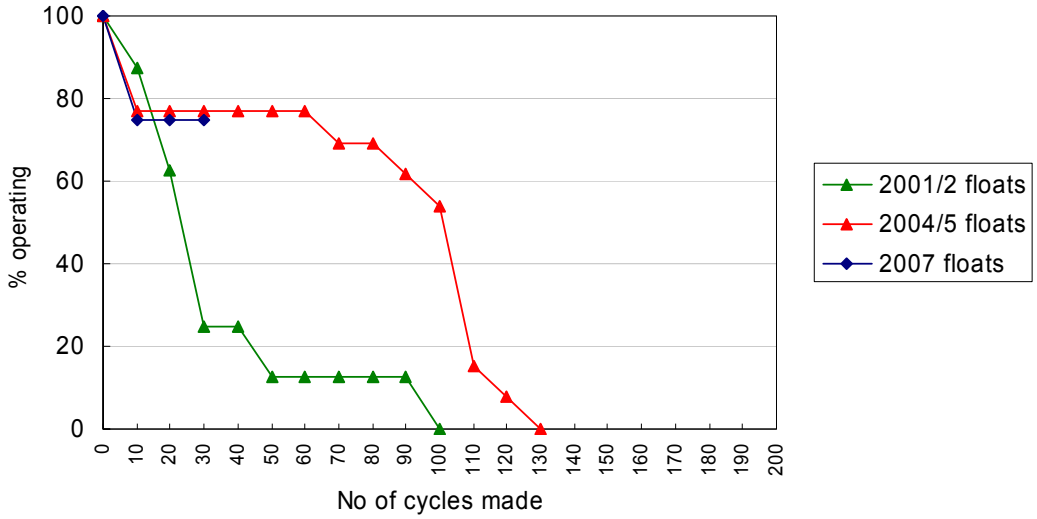

Figure 9. Showing the % numbers of Provor floats, deployed by period, operating. There were no deployment failures with all floats cycling to 2,000m depth.

Technical collaboration with CSIRO Marine

As a result of the relatively high number of early float failures in 2002 and 2003, UK Argo increased its technical support at the Met Office and in 2004 a technical collaboration with CSIRO Marine was initiated. From summer 2004 all Apex floats received in the UK have been bench-tested before deployment and more rigorous deployment checks instigated.

In collaboration with CSIRO an engineering web-site for UK (http://www.cmar.csiro.au/argo/tech/IndexUK.html) and Australian floats has been established to help monitor the performance of deployed UK (and Australian) floats, as illustrated in Figure 10. The web-site allows a wide range of engineering parameters (battery voltage at park, pump battery voltage, surface piston position, air bladder pressure etc.) for each float to be displayed. This information allows the health of our floats to be determined and can also be used, in many cases, to indicate the likely cause of float failures, e.g. premature battery decline (see Figure G.1). Through this collaboration we are able to better monitor the health of the UK floats and, with CSIRO, to provide a collective view on technology improvements required.

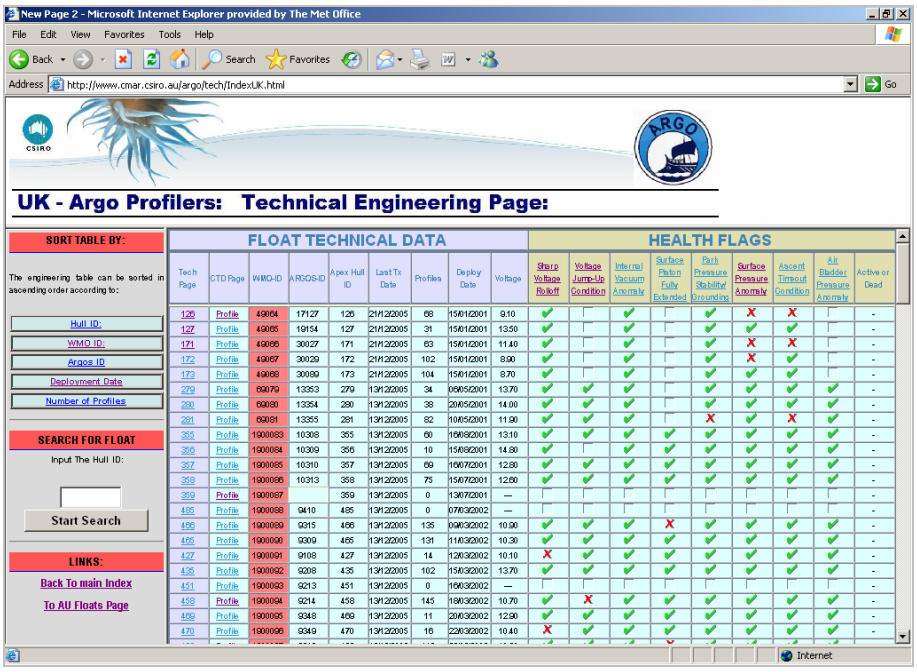

Figure 10. Main technical engineering page for UK floats from the CSIRO developed web-site.

Float technology developments

Future float developments include the use of new sensors; oxygen and CO_2 sensors have already been tested by others, as have measurements of ocean mixing based on microstructure observations. Floats have also been used to measure changes in velocity shear in the upper ocean beneath a passing hurricane. New communication systems (e.g. Iridium) allowing greater data transmission capacity coupled with more accurate GPS positioning will enable more detailed profiles to be transmitted with surface time reduced to minutes rather than hours (hence reducing the effect of biological fouling of the salinity sensor).

At present Apex floats cease sampling at around 4 m depth in order to avoid pumping 'contaminated' surface water through the salinity sensor, as even in the open ocean a thin film of oils can be present at the surface. One development that has been advocated by the GHRSST (GODAE High Resolution Sea Surface Temperature) Project Office and the Met Office is to enable floats to be able to sample temperature data to the surface in order to better resolve the near surface mixed layer vertical structure – and to help better elucidate the differences between ship and drifter SST measurements which provide the climate SST record. New designs are currently being tested (by University of Washington) with a near surface CTD that will work above 5 db, this work is funded by the NASA Aquarius program (towards calibration of satellite surface salinity measurements). This new sensor is deployed together with the current sensor to allow calibration on each profile. Other techniques being developed include sampling modifications to allow temperature only sensing in the top 5 db.

For deployments in ice covered regions Apex floats can be provided with ice-avoidance algorithms as floats are susceptible to being damaged at the surface by buffeting by ice in rough seas. These identify environmental conditions from the profile measurements in which surface ice is likely to occur and prevent the float from surfacing. 4 UK floats with ice-avoidance were deployed in the Weddell Sea in early 2007 and these all successfully reappeared after the austral winter, although the data from while the float is under ice cannot

be recovered. However, acoustic tracking and onboard data storage can permit measurements under the seasonal Antarctic ice cover to be recovered.

The Argo data system

A fundamental principle of Argo is that all Argo data are freely available, without any restrictions on use, both in real-time and after scientific (delayed-mode) quality control. This open data policy, in line with WMO Resolution 40 and IOC Resolution XX-6, is aimed at ensuring the widest possible use of the data. However, without adequate data processing the Argo data are of little use to the wider community. Real-time data are required by operational users (e.g. for ocean forecasting) and delayed-mode data (after more careful QC to correct for sensor offsets and drifts) for climate studies.

Over the last 5 years Argo has built an efficient data management network of national centres that provides data in real time (90% of profiles available within 24 hours and almost all within 48 hours) and delayed mode, from two global hubs, one hosted by Coriolis (France) and the other by GODAE (USA). Operational weather and climate centres also get the real-time data from the WMO Global Telecommunications System (GTS).

In real-time the aim is to deliver data to users (mostly operational forecast centres, such as the Met Office) within 24 hrs, with gross errors in the profiles removed, flagged or corrected. These data are disseminated through the GTS and are also available via the internet from the two, mirrored Argo global data assembly centres (GDACs) in the USA and France.

The delayed-mode data stream involves scientists who compare float data with reference data sets and apply regional oceanographic expertise and float to float intercomparisons to identify any sensor drift and the most-likely salinity offset for each profile. The suggested corrections are then made available from the global centres, with an expectation that these data will be available within 6 to 12 months of data collection. Regional centres are being developed that will start to assemble data and create regional products.

UK Argo Data Centre

BODC operate the UK Argo Data Centre (http://www.bodc.ac.uk/projects/international/Argo/) and have two distinct roles for UK Argo. They act as the data centre for UK floats in the Argo programme regardless of their location and as the Regional Centre for the Southern Ocean in collaboration with the CSIRO, Australia.

Real-time data processing and issue to the GDACs

As noted above, the UK Argo Data Centre, processes all our float data. New floats are added into the system as they are deployed and metadata compiled; a metadata netCDF file is generated for each float and forwarded to the GDACs. An automatic near-real-time processing system has been developed and is operational. This downloads the raw (hexadecimal) data from CLS, decodes the data stream, carries out an agreed suite of automatic quality control tests (adding quality flags to the data as necessary), and generates profile and trajectory data files in the internationally agreed netCDF formats. There is also a visual inspection of the profiles. The files are sent to the two GDACs, generally within 24 hours of receipt, and are also available from the UK Argo Data Centre web-site via an interactive map interface. The web-site is automatically updated daily with UK float status information, a map of current float positions and temperature and salinity profile plots.

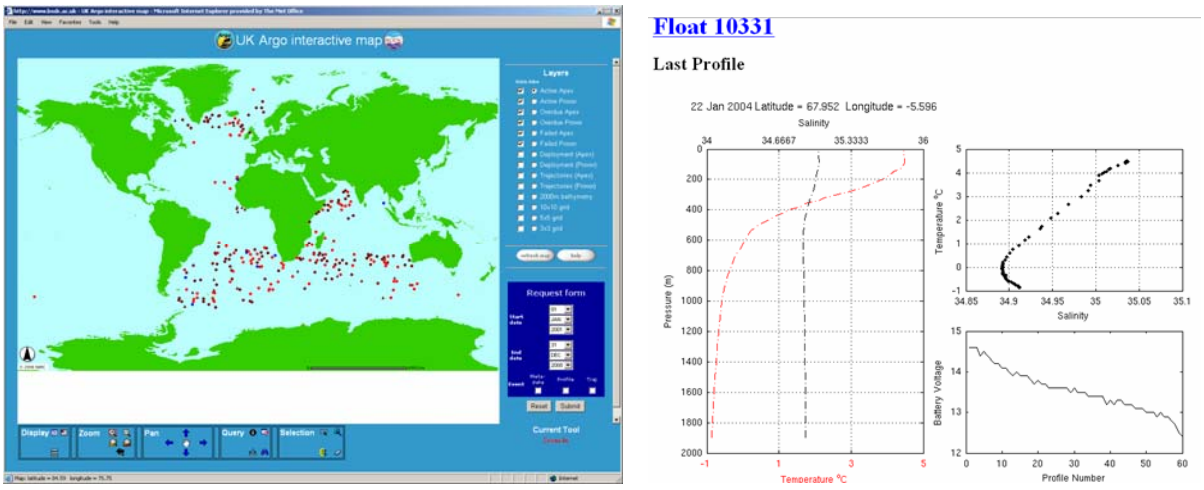

Figure 11. Example of web interface for UK float data on the UK Argo Data centre web-site.

Real-time data processing and issue to the GTS

Data from all working UK floats are also issued to GTS in WMO TESAC format. All float data received over GTS are assimilated daily into the operational FOAM system run by the NCOF and also used in the GLOSEA (Global Seasonal) coupled ocean-atmosphere general circulation model for seasonal forecasting run at the Met Office. GTS is the primary mechanism for receipt of real-time data (float data, ship data etc.) used in the Met Office's forecasting systems.

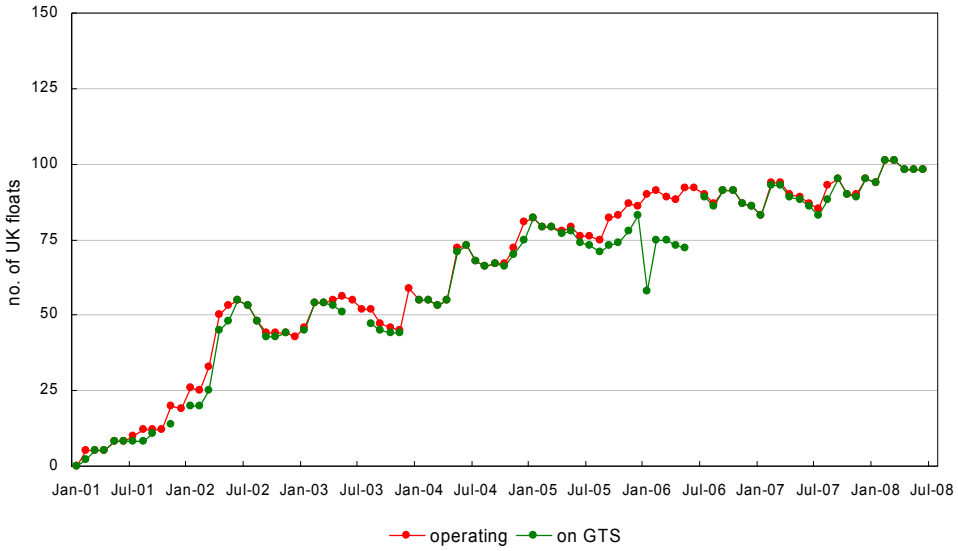

Figure 12. Number of UK floats operating (red) and reporting data on GTS (green) since the start of 2001.

Figure 12 shows the numbers of UK floats reporting data to GTS and indicates that to summer 2005 profiles from around 95% of operating UK floats were on the GTS (as assessed against those available on the GDACs). However, this (target) figure was not achieved during the second half of 2005 and first half of 2006. Up to end June 2006 all UK float data were issued to GTS through Meteo-France, with TESACs being generated by CLS (for the older 20-bit Apex floats) and Coriolis (for Provors and the newer 28-bit Apex floats). Although it was decided at the outset that we would use the 'free' GTS dissemination service

provided by CLS, our experience showed this was not optimal (missing profiles and inability to decode the newer 28-bit Apex and Provor floats).

As a result in summer 2006 we implemented a UK system to issue the float data to GTS. BODC routinely generate in real-time netcdf profiles which are issued to the GDACs, at the same time as these are generated (twice daily) TESAC messages are now created and automatically emailed to the Met Office's message switching system. Here the TESACs are automatically routed to the GTS. This new system was tested in late June 2006 and implemented operationally at end July after a period of parallel running with CLS, Coriolis and Meteo-France. Since then data from over 99% (on average) of our floats have been disseminated on GTS. This system should also allow for a more rapid transition to the use of BUFR code as TESAC is phased out over the coming years.

Delayed-mode data

Delayed-mode quality control for float salinity is undertaken by the UK Argo Data Centre to check sensor drifts and offsets and for calculating adjustment estimates and related uncertainties. The Wong, Johnson, Owens (WJO) software estimates background salinity on a set of fixed standard isotherms, then calculates drifts and offsets by time-varying weighted least squares fits between vertically-interpolated float salinity and estimated background salinity. This software has been installed at BODC and is being used in the delayed-mode QC process. Once the semi-automatic process is complete, the output is checked by the Principal Investigator to ensure that the statistical recommendations are appropriate and that the associated uncertainties are realistic. A total of 4,492 delayed-mode profiles have been submitted, this is about 40% of all floats available for delayed mode processing (i.e. excluding floats that have been operating for less than 18 months).

Southern Ocean Regional Argo Centre (SORAC)

The UK has long-standing scientific interests in the Antarctic and Southern Ocean, and the rationale for UK involvement in the SORAC is to ensure that the UK science community has access to the best quality data. The SORAC is a collaborative effort between BODC and CSIRO with BODC taking the lead on the Atlantic sector and (western) Indian Ocean with CSIRO focusing on the region around Australia, although there has been a lack of manpower to cover all of the Southern Ocean. However JAMSTEC have recently offered to help in looking after activities in the South Pacific and its southward extension and the University of Washington has volunteered to contribute in the Indian Ocean sector. During 2005 the Southern Ocean ARC web-site http://www.bodc.ac.uk/projects/international/argo/southern_ocean/) was improved, with a dynamic interactive map showing the locations of all floats in the Southern Ocean over the last 30 days, together with output from the Met Office's ¼° Antarctic FOAM.

Euro-Argo

As noted earlier Euro-Argo is recognised as being an important research infrastructure and forms part of the ESFRI 'Roadmap'. The Euro-Argo project is a 30-month project (which started January 2008) to develop and recommend a European infrastructure to enhance the collective ability of the European nations to contribute to Argo, and by working together to be able to do so more efficiently in the future. Funding for Euro-Argo is being provided through EC FP7-Infrastructures. For the UK the organisations involved are NERC (through the National Oceanography Centre, Southampton and the British Oceanographic Data Centre) and the Met Office.

The aim is to develop the infrastructure to the level where the European partners have the capacity to procure and deploy ~250 floats per year, the ability to monitor these floats, ensure all float data can be processed (both in real-time and delayed-mode) and to clear the present backlogs in the data processing system. With a mean float lifetime of 3¾ years such a European contribution would support approximately ¼ of the global array and provide an additional 50 floats per year for enhanced coverage in the European and marginal seas. This will require both national and central (EU) support for Argo, and it has been suggested that the EU (GMES) could fund ½ of the floats required (~100 per year) to support the global array with national contributions supporting around 150 floats per year (as at present).

It is expected that the Euro-Argo project will define the capability required (i.e. where a common infrastructure would be beneficial), with agreements on governance and legal issues, ready for implementation/signature following completion of the project in 2010. As indicated above the Euro-Argo infrastructure will build on the national Argo programmes and will require long-term commitments by all partners.

By entraining more European countries into Argo, and securing new EU (GMES) funding for floats, it is expected that the European-wide contribution to Argo will be increased (to the 250 floats per year level) and put on a more secure basis. This will help secure the longer-term operation of the Argo 3,000 float array, and its continued ability to deliver valuable data to operational and research users. However, securing a long-term UK funding commitment to Argo and Euro-Argo will be critical to both Euro-Argo and to the international Argo array.

Annex A

Impact of Argo data on FOAM predictions – Matt Martin, NCOF

A set of integrations has been performed with the FOAM system for the period January 2001 to July 2005. The 1° global model, 1/3° North Atlantic and Arctic model and 1/9° North Atlantic model have all been run for this period, starting from operational FOAM analysis fields and forced by 6 hourly surface fluxes from the Met Office NWP system. These integrations have been run with assimilation of all in situ temperature and salinity data (ALLTS), and a repeat of the ALLTS run but with the Argo data withheld (NOARGO).

The impact of the Argo data on the FOAM system is illustrated in figure A1 which shows RMS errors of temperature and salinity analyses from the 1/9° North Atlantic model when compared to observations which haven't yet been assimilated but are valid within 24 hours of the analysis. The ALLTS run (black) has much less error in temperature over all of the top 1,000 m when compared with the NOARGO integration (orange). The salinity errors are most significantly reduced by the Argo data assimilation in the top 600 m. These results show both the importance of the Argo data and the impact of the data assimilation on the model fields.

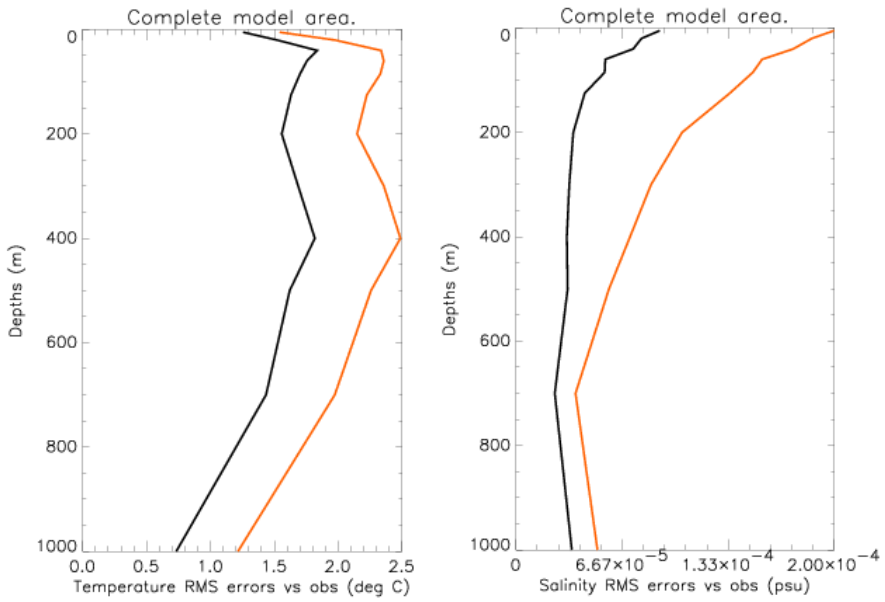

Figure A1. RMS errors in (left) temperature (°C) and (right) salinity (psu/1000) analyses compared to in situ profile observations before they are assimilated, averaged between January 2001 – July 2005. Results are shown for the ALLTS run (black) and the NOARGO run (orange).

Figures A2 and A3 show the average differences between the FOAM 1/9° model temperature and salinity fields and the Levitus climatology at 1,000 m depth. With the Argo data withheld, there are large anomalies relative to Levitus with a significant warm and salty bias in FOAM throughout much of the North Atlantic and a cold and fresh bias in the east of the region. Assimilating the Argo data controls these biases to a large extent.

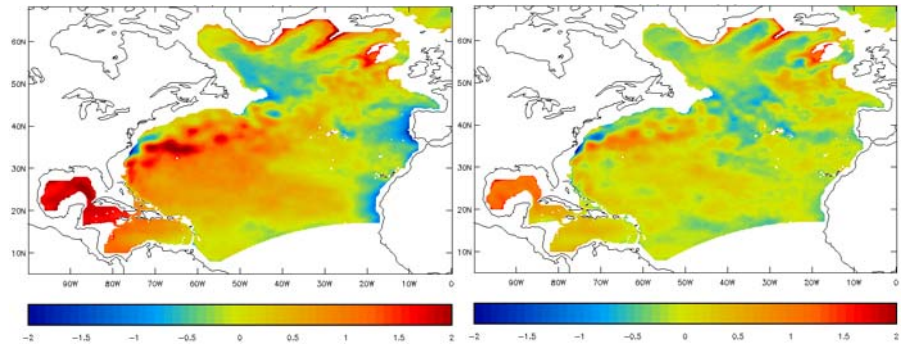

Figure A2. Average potential temperature difference (°C) between Levitus and model at 1,000 m depth for (left) NOARGO run and (right) ALLTS run.

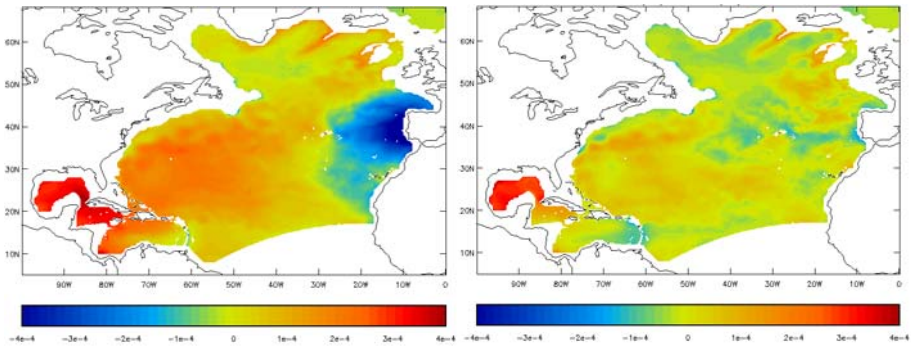

Figure A3. Average salinity difference (psu/1000) between Levitus and model at 1,000 m depth for (left) NOARGO run and (right) ALLTS run.

Figures A4 and A5 show the average temperature and salinity increments which are being put into the model by the data assimilation at 1,000 m. Without Argo data, these average increments are much smaller in temperature and virtually zero in salinity. When the Argo data is assimilated the increments show how much work the data assimilation is having to do to control the model biases. These biases are thought to be due to the vertical advection scheme used in these experiments (QUICK) which is highly diffusive. The operational models will be updated to use centred differencing in the vertical later this year.

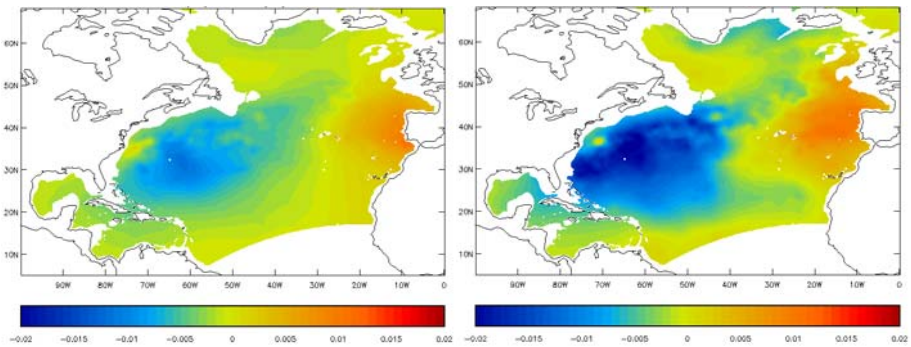

Figure A4. Average temperature increments (°C) at 1,000 m depth for (left) NOARGO run and (right) ALLTS run.

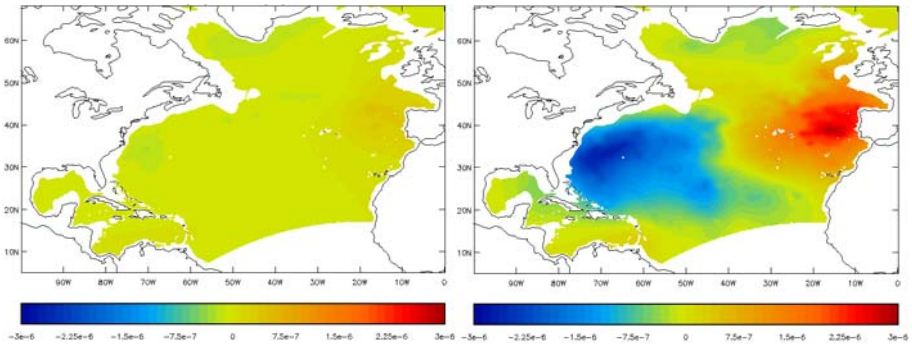

Figure A5. Average salinity increments (psu/1000) at 1,000 m depth for (right) NOARGO run and (left) ALLTS run.

Use of Argo data for mixed layer prediction in FOAM – David Acreman, NCOF

Argo data allow validation and tuning of mixed layer models to be performed with a very wide geographical coverage. Figure A6 shows results from validating three mixed layer models using data from a single Argo float. This float was close to the location of OWS Papa which is believed to be a good location for testing 1D mixed layer models as advective processes are thought to be weak.

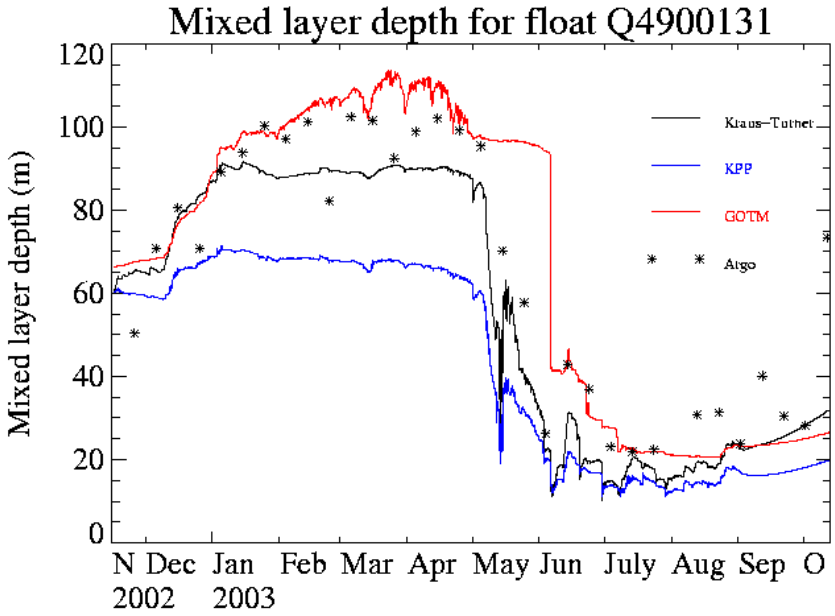

Figure A6. Mixed layer depth diagnosed from float Q4900131 and as predicted by 3 different mixed layer models.

By combining results from validation using many floats a much more complete picture of mixed layer model performance can be built up. The relative ease with which one dimensional mixed layer models may be validated against Argo data allows detailed tuning of mixed layer models to be performed which is used to inform parameter choices in more complex applications such as the Met Office FOAM system.

With assimilation of Argo data the error in the depth of the mixed layer predicted by FOAM is significantly reduced, see Fig. A7. The improvement in prediction is seen over the previous 4 years with the increase in available Argo data.

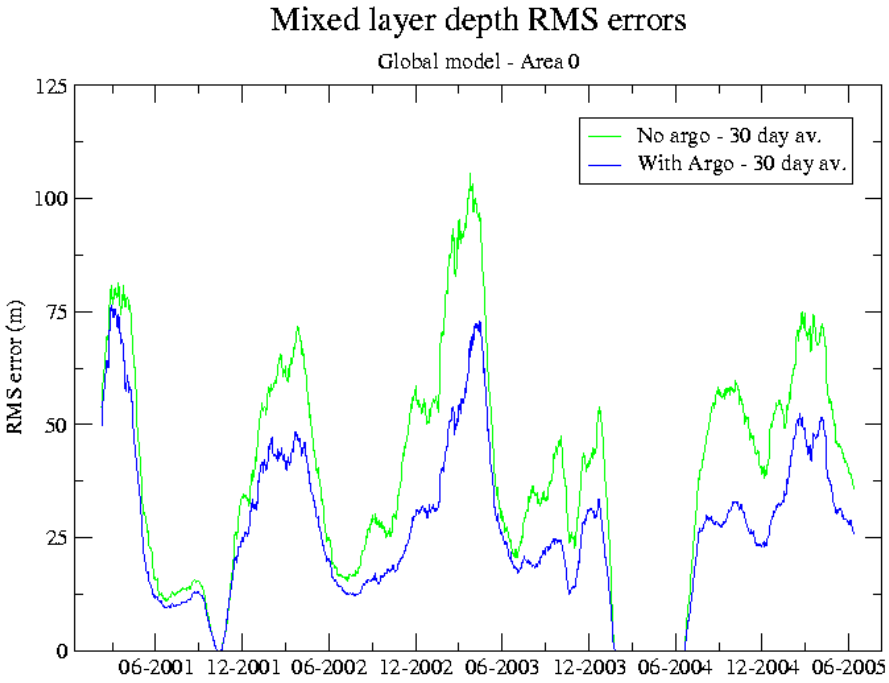

Figure A7. RMS error in predicted mixed layer depth over the past 4 years, both with and without assimilation of Argo data.

Annex B

The impact of the Argo ocean profiling array on seasonal forecasts - Matt Huddleston, Sarah Ineson, Bruce Ingleby (Hadley Centre) and Malcolm MacVean (ECMWF)

Long-range forecasting technology uses observations of the ocean to initialise comprehensive global coupled (ocean-atmosphere) forecast models. Since the advent of the Argo profiling float observation programme, the number of observations of temperature and salinity available in real time for this process has increased markedly and the utility of these observations has been explored in three areas: observation density and quality control, the impact of the observations on ocean analyses and the impact of these ocean analyses on seasonal range coupled model forecasts.

An experiment has been performed to try and assess the impact of Argo on seasonal forecasting. The number of Argo observations varies through the experiment, from approximately 800 profiles per month available globally in 2000 to more than 4,000 in 2004. A comprehensive quality control procedure recently developed at the Met Office has been used to prepare the observations for assimilation, rejecting 1.5% of temperature and 4% of salinity profiles in this study, although this has now been reduced to less than 1% of Argo observations in the latest quality control system for both variables.

Six ocean analyses were produced using an ocean GCM and a data assimilation system in data-withholding experiments over 2000-2004. The impact of each observation type is tested by withholding it from an ocean analyses. There are clear impacts on the analyses from the Argo observations as the data density increases – both positive and negative depending on the oceanic regime and it's response to the data assimilation methodology. Argo data is clearly more accurate than XBT data and the global coverage of Argo acts to remove bias in the analysis derived from the XBT data and the ocean model / atmospheric forcing.

Whilst the 5 year retrospective forecast period is short in terms of accounting for the variability in forecast skill from, e.g. El Niño, regions of positive (see Figure B1), negative and neutral impacts on SST forecasts initialised from the different observation types can be found. A more general assessment of predictability of ocean heat content (in terms of vertically averaged temperature) shows a positive benefit for all lead times and forecast seasons from forecasts initialised using Argo data as shown in Table B1.

It is clear that care is needed in the assimilation of profile data in some regions and especially in the use of salinity data. Given this, Argo profile data positively benefit seasonal forecast performance and are beneficial to the three areas of seasonal forecast production examined.

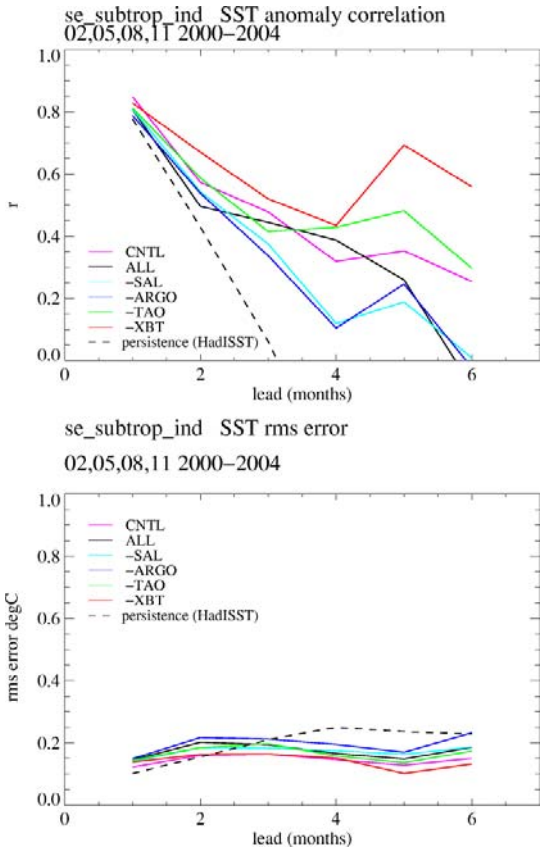

Figure B1. Impact of ocean analyses on Indian Ocean SST forecasts (correlation and RMS errors versus forecast lead time validated against HadISST) in an area west of Australia (80-120° E, 10-30° S) for all start dates and lead times. Withholding Argo data in this area clearly decreases forecast skill.

	Persistence	CNTL	ALL	-SAL	-ARGO	-TAO	-XBT
Feb 2-4	0.57	0.39	0.64	0.57	0.55	0.62	0.56
Feb 4-6	0.37	0.24	0.44	0.39	0.38	0.43	0.38
May 2-4	0.59	0.37	0.64	0.55	0.49	0.62	0.57
May 4-6	0.43	0.25	0.46	0.40	0.38	0.42	0.45
Aug 2-4	0.55	0.37	0.67	0.58	0.55	0.66	0.60
Aug 4-6	0.42	0.32	0.51	0.45	0.42	0.52	0.48
Nov 2-4	0.56	0.43	0.70	0.60	0.58	0.68	0.64
Nov 4-6	0.34	0.31	0.51	0.44	0.43	0.49	0.47
Mean	**0.48**	**0.34**	**0.57**	**0.50**	**0.47**	**0.55**	**0.52**

Table B1. Global mean forecast anomaly correlation coefficients (ACC) of 360m vertically averaged temperature for various start dates in comparison to an ocean analysis using ALL data. Feb 2-4 indicates the mean of five forecasts initialised 1st Feb for 2000-2004 for the forecast months 2 to 4 (March, April and May). Again, withholding Argo data is detrimental to forecasts of upper ocean temperature.

Annex C

The importance of Argo for climate research - Sheila Stark, Richard Wood (Hadley Centre) and Brian King (NOCS)

The continuous time-series of ocean temperature and salinity that Argo will provide are an essential tool if we are to understand the impact of climate change on the ocean. The full value of Argo for climate research will only be realised when multi-year or decadal time-series are available; here we give examples of the questions that Argo can help answer, which are inaccessible with currently available methods of observation.

First, we use a climate model (HadCM3) to aid interpretation of recent observations of salinity changes in the South Indian Ocean. Sub-Antarctic Mode Water (SAMW) is a globally important water mass, the export of which from the Southern Ocean forms part of the upper limb of the global overturning circulation. Hydrographic observations of SAMW collected at 32° S in the Indian Ocean in 2002 show that the water mass was warmer and saltier on isopycnals than in 1987. This is in contrast to the isopycnal freshening which was observed between 1962 and 1987. The response of HadCM3 under a range of 20th century forcing scenarios has been studied; CON the control experiment with no applied forcing, NAT, where the model is forced with historical changes in solar irradiance and volcanic emissions, ANT where anthropogenic greenhouse gas and ozone levels are used, and ALL which combines the two. The model does reproduce the observed freshening between the 1960s and 1980s in both ANT and ALL but the subsequent salting is not seen in either experiment. This makes it hard to explain the observed isopycnal salinity changes as a forced response.

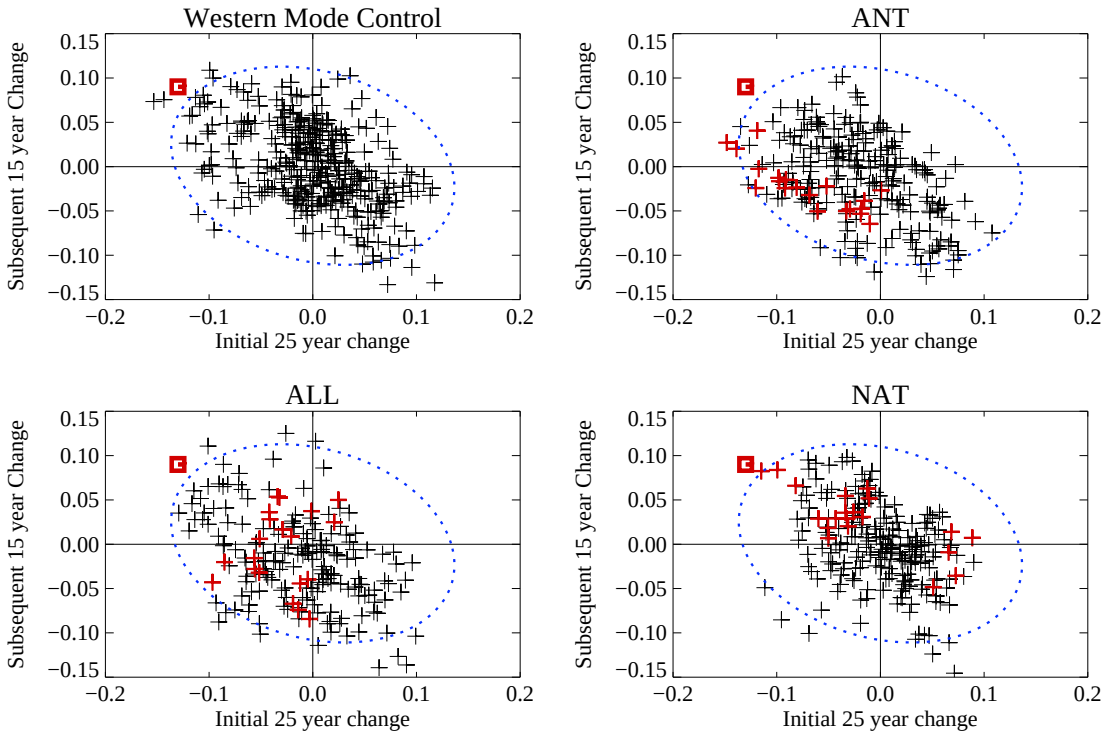

Figure C1. Distribution of 40 year changes in the HadCM3 control run (CON) and each forced experiment. The observed changes are shown by the red square and the comparable periods from the forced experiments are highlighted by red crosses. The blue ellipsoid illustrates 2.5 standard deviations from the mean of the distribution.

Although the observed salinity changes are too few to define SAMW variability they indicate changes in isopycnal salinity of order 0.1psu over 15 to 25 year timescales. Variability of this magnitude is seen in all of the forced experiments, on a range of timescales, as well as in CON. Figure C1 shows the distribution of 40 year isopycnal salinity changes decomposed into a 25 year change and its subsequent 15 year change for each overlapping 40 year period in the control and each forced experiment. It is evident from Figure C1 that the observed changes are unusual in the CON distribution and in each of the forced experiments. The ANT and ALL distributions exhibit a freshening trend but the control and NAT distributions show oscillating mode water salinity which is not inconsistent with the available observations. Therefore we have no reason to conclude that the observed SAMW changes are not due to internal variability. The lack of higher frequency observations, such as could be provided by Argo, limits our ability to make a more definite attribution statement than this.

HadCM3 simulations of SAMW in the 21st century show the water mass exhibiting a strong long term freshening trend, the result of increased heat and freshwater fluxes at high latitudes in the Southern Ocean. However, despite the long term trend, the water mass continues to exhibit significant decadal variability making it vital that high frequency observations are collected to allow any climate change signal to be clearly distinguished from the background noise.

The second example focuses on early detection of climate change signals in the meridional overturning circulation (MOC). Early detection of MOC change by continuous monitoring is the primary goal of the NERC funded RAPID array at 26.5° N in the Atlantic. However, there still exists, as described above for SAMW, the difficulty of determining whether an observed MOC change is unusual or consistent with internal climate variability. Models show that the MOC is a noisy field (see Figure C2) as a result of, for example, fluctuations in surface winds, making long term trends hard to detect.

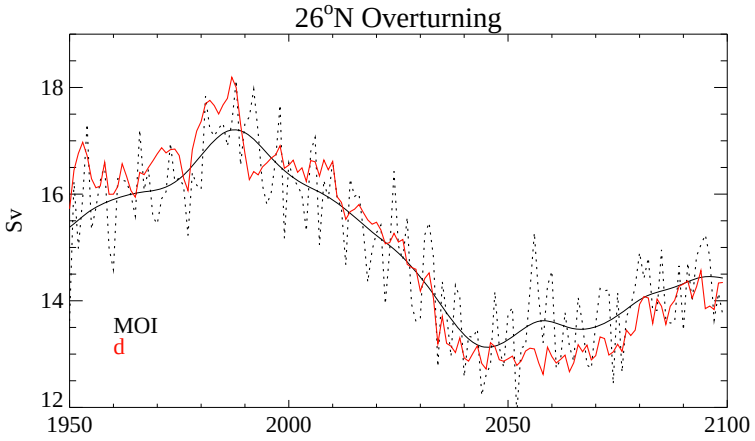

Figure C2. Time-series of the MOI in a HadCM3 experiment with anthropogenic forcing in the 20th century and IPCC B1 scenario forcing to 2100. The annual mean time-series is shown by the dotted line while the solid line shows the same series with high frequency variability filtered out. The MOI reconstructed from our optimal detector d is shown in red.

We have used HadCM3 to demonstrate that it is possible, in the model at least, to improve detection of anthropogenic MOC change using a multivariate observing system, rather than sampling at 26.5° N in isolation. Sub-surface hydrographic

observations tend to have a better signal to noise ratio (STNR) than the MOC. Three such observations, chosen from an original selection of approximately 350 on the basis of their linear correlation with the MOC at 26.5° N (referred to as the MOI) at timescales of 40 years or longer, are used in conjunction with the MOI as the multivariate detector *d*. Detectors comprising between 1 and 15 observations were considered. It was found that despite the highest STNR being seen for a 5 observation system the best overall performance was seen if only 3 were included. The detector optimises the detection time of MOI change by reducing the STNR, such that *d* has a better STNR than the MOI itself. The 3 observations which along with the MOI comprise our detector are:

1. Potential temperature at $\sigma_\theta = 28.0$ in the Norwegian Sea.
2. Salinity in the northern subpolar gyre (a combined sampling of the dense northern overflows).
3. Potential temperature between 0 - 250 m along 20° W (30° S - 30° N).

The resulting detector correlated well with the MOI (-0.89). The reconstructed overturning at 26.5° N is much less noisy than the MOI itself (Figure C2) and tracks well the anthropogenic weakening seen at the start of the 21st century. The main advantage offered by *d* is improved detection times of an unusual change. The model shows that if the MOI alone is sampled 18-19 years of data is required for a clear signal to be detected, but only 9-10 years is required for *d*. The higher STNR of our system offers improved 'early warning' capability for changes in the MOC.

All three of the hydrographic observations included in *d* could be measured using Argo floats, many of which are already deployed in the relevant areas. While the potential usefulness of a system such as *d* is clear in HadCM3, further work is needed to see how well it could translate to the real ocean. The first two observations on the above list are sampling the properties of the water masses which are precursors to North Atlantic Deep Water (NADW). The observed importance of the Nordic Seas and overflows to NADW and the THC make it likely that these are robust properties for THC change in the real ocean, as well as in HadCM3. At present lack of observations means that observing system design can only be done with models. To verify the usefulness of these model designs Argo time-series could be pivotal.

Sustaining the Argo time-series for long enough to reap the full benefits for climate science is a challenging goal. Here we have given two examples where Argo could give us an understanding of the ocean which traditional hydrographic observations cannot. To detect climate change signals it is necessary to fully understand the oceans internal variability, which is at present a huge gap in our knowledge. This can only be done via continuous monitoring of the type offered by Argo. We have shown the potential benefits of Argo in the North Atlantic, a region which is relatively well sampled. In more data sparse regions the pay back could be even greater.

Inter-annual changes in thermocline properties in the subtropical Indian Ocean – Brian King and Elaine McDonagh, NOC Southampton

In March 2002, a transoceanic hydrographic cruise at 32° S in the Indian Ocean revealed changes in Mode Water properties since the previous occupation of the section in 1987. Salinity had increased on isotherms warmer than 10 °C, with a maximum salinity change exceeding 0.04 at the 13 °C isotherm in the western part of the basin. Argo floats deployed during the cruise confirmed that the change was consistent over a large region in the south-west Indian Ocean. Data reported by the floats during the subsequent 3 years show that floats are capable of monitoring the

changes with inter-annual resolution. There was further increase in salinity during 2002 and 2003, but a levelling off during 2004.

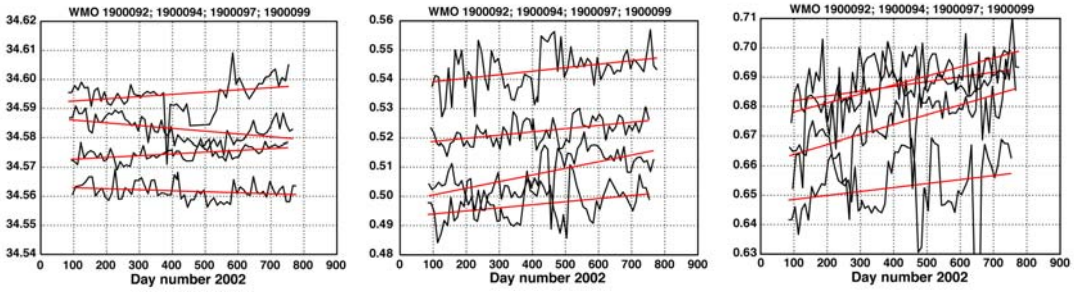

Figure C3. Salinity changes, on the θ = 8° (left), 12° (middle) and 13° surfaces, for 2002 and 2003 for 4 different floats in the South Indian Ocean.

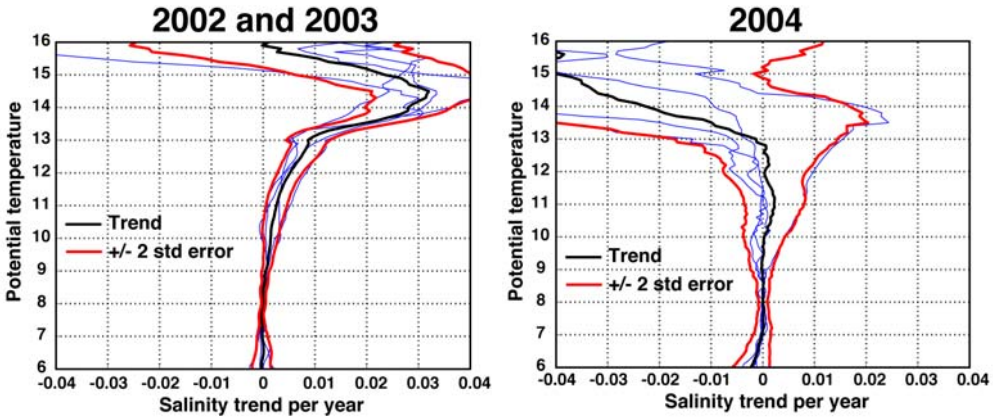

Figure C4. Salinity trend for 2002 and 2003, and 2004 showing salting in 2002 and 2003 and stability during 2004.

So long as Argo float density and data quality are sustained, Argo will provide a means of monitoring the properties of thermocline and intermediate waters, at all timescales relevant to climate. As the array nears completion in all basins, Argo will enable a direct comparison to be made between the state of the global upper ocean in the present decade and in the 1990s. This will be possible within the next two years.

Development of a new global sub-surface ocean analysis of temperature and salinity (HadGOA) for climate – Matt Palmer, Tara Ansell, Simon Tett (Hadley Centre) and Keith Haines (ESSC, University of Reading). (Updated July 2008)

HadGOA is a new ocean analysis of historical temperature and salinity suitable for climate model validation, evaluation of historical ocean heat content variability and ocean climate monitoring. It is based purely on observed data taking quality controlled data from the Met Office system developed for the EC funded ENACT (Enhanced Ocean Data Assimilation and Climate Prediction) project. The current version (EN3) uses observations from the WOD05 ocean database, with additional data from WOCE, the BMRC and CSIRO (Australia), PMEL (USA), the GTSPP and the Argo GDACs. A sustained Argo array is essential for ongoing climate model assessment and the development of a near real-time monitoring and attribution system.

A first HadGOA product has been developed, which grids ocean depth on isotherms. This approach helps to better understand the mechanisms behind ocean heat content changes (Palmer et al, 2007[6]). Theory and results suggest that warming above isotherms is generally indicative of changes in air-sea heat fluxes and that changes in isotherm depth are more indicative of ocean circulation changes. In conventional fixed depth analyses, these two signals are merged. This is demonstrated in figure C5. Warming above the 14 °C isotherm (Figure C5b) shows a much more globally uniform spatial pattern than warming relative to a fixed depth (Figure C5c). Trends in isotherm depth (Figure C5d) show large spatial in-homogeneity and leave their imprint in the fixed depth trends.

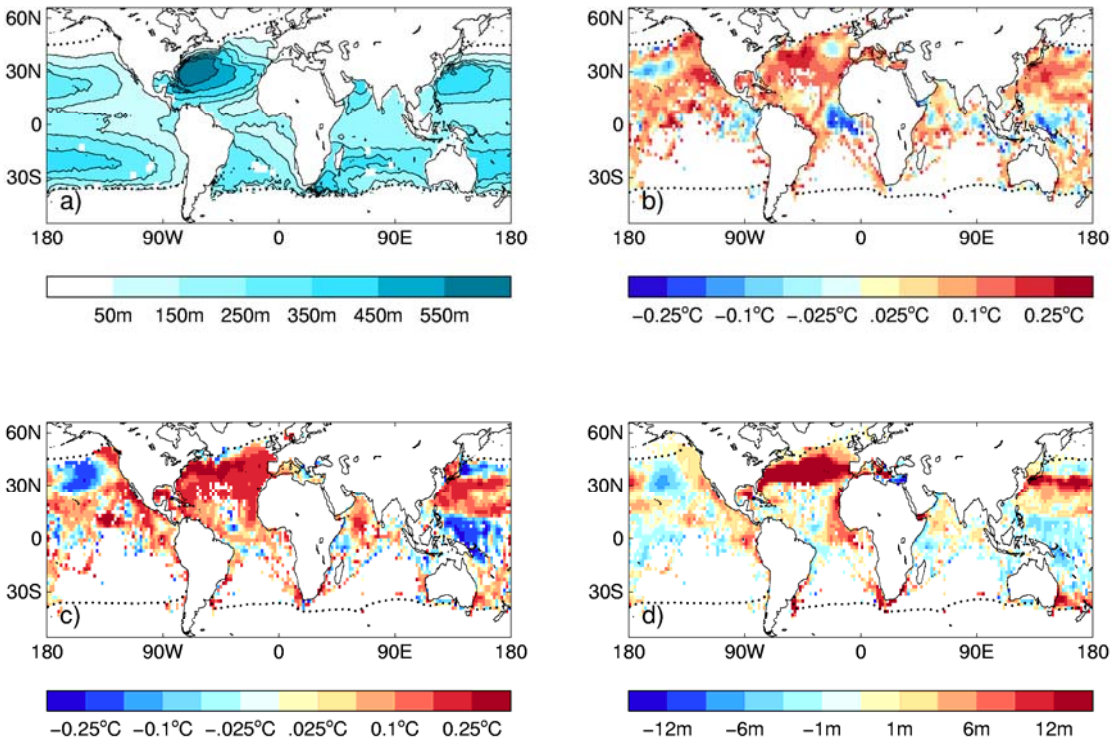

Figure C5. (a) The July–August–September mean depth of the 14 °C isotherm over the period 1956–2004. (b) Trend (°C per decade) in mean temperature above the 14 °C isotherm. (c) Trend (°C per decade) in mean temperature above 220 m. (d) Trend (m per decade) in depth (positive is deepening) of the 14 °C isotherm. All trends are computed separately for each 2°×2° grid box over the period 1965–2004. Figure taken from Palmer et al [2007].

The warming trend analyses above highlight the paucity of the historical data, particularly in the Southern Hemisphere, for estimating patterns of ocean heat uptake. Argo is revolutionising our ability to observe and understand ocean climate; since mid-2002 Argo has been the largest single source of ocean profile data, not only being more numerous but also deeper and more accurate, and with salinity information. In the Southern Ocean, a climatologically important region, Argo now provides data at 50 times the pre-Argo rate. Hence the accuracy of key ocean data analyses, such as HadGOA, will be very dependent on the continued availability of Argo data.

[6] Palmer, M. D., K. Haines, S. F. B. Tett, and T. J. Ansell (2007), Isolating the signal of ocean global warming, Geophys. Res. Lett., 34, L23610, doi:10.1029/2007GL031712.

Annex D

How useful is Argo for investigation of interannual variability in the North Atlantic heat content? - Rachel Hadfield, Neil Wells and Simon Josey (NOC, Southampton)

The accuracy of Argo based estimates of the North Atlantic Ocean Heat Content (OHC) is investigated. The work carried out involved sub-sampling a model temperature field to the Argo sampling density and then using an optimal interpolation scheme to obtain a gridded temperature field. OHC was calculated from the sub-sampled, interpolated and full model temperature fields. Comparison between the two OHCs gives an indication of the expected errors in using the Argo dataset to quantify OHC.

It was found that away from regions of high mesoscale activity, complex bathymetry and low sampling density, the change in mixed-layer OHC was accurate to within 10 Wm^{-2}. However, within the Gulf Stream region, north of 50 °N and south of 25 °N, errors were in excess of 50 Wm^{-2}. In these areas Argo cannot be used to investigate interannual variability in OHC. An experiment was undertaken to determine the critical number of floats required to reduce errors to less than 10 Wm^{-2} on a 10x10° grid throughout the North Atlantic. The relationship between RMS differences and float numbers was found to be complicated, with dependence on the distribution of the float profiles, although as expected the differences decreased with increasing sampling density.

Figure D1 shows the RMS difference between the mixed layer OHC change based on the full model temperature field and the sub-sampled gridded temperature field at different sampling densities for a region of the North Atlantic where errors are low. For each sampling density considered, the model temperature field was randomly sub-sampled ten times to provide an estimate of the errors. The error bars are quite large indicating a high dependence on the distribution of the sampling field. The 1999, 2004 and Argo target densities are also plotted to put the sampling densities into context (the x axis is number of profiles in the North Atlantic in 24 months). Note that the 1999 and 2004 lines indicate sampling after quality control procedures have been applied.

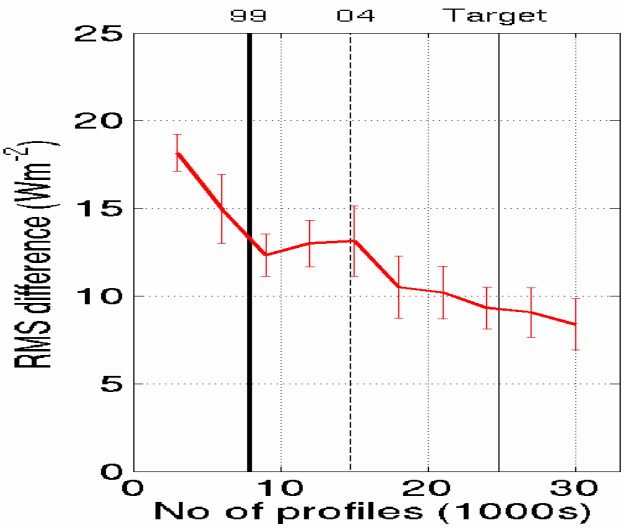

Figure D1. Accuracy of Argo ΔOHC for different sampling densities.

Recent changes of heat content in the North Atlantic Ocean - Neil Wells and Vladimir Ivchenko – NOC, Southampton

Whether the North Atlantic Ocean is warming or cooling is an important question both in physical oceanography and climate change. Levitus et al. (Science, 2000) has shown a warming of the upper 300 m of the North Atlantic between 1975 by 1998. The Argo floats provide an accurate and stable instrument for determining the tendencies in heat content from the surface to 2000 m from 1999 to the present. However there are both spatial and temporal gaps in this data set. For this reason we combine these observations with a climatology (Levitus (2001), Gouretski and Koltermann (2004)). By this method we can estimate the anomaly of heat content (AHC) in the North Atlantic and all of its smaller sub-domains for the period 1999-2005. The results of our calculations are stable: removing a part of the data does not substantially change the estimated AHC. The upper 1,500 m layer of the North Atlantic shows persistent negative values during the whole 6.5 year period.

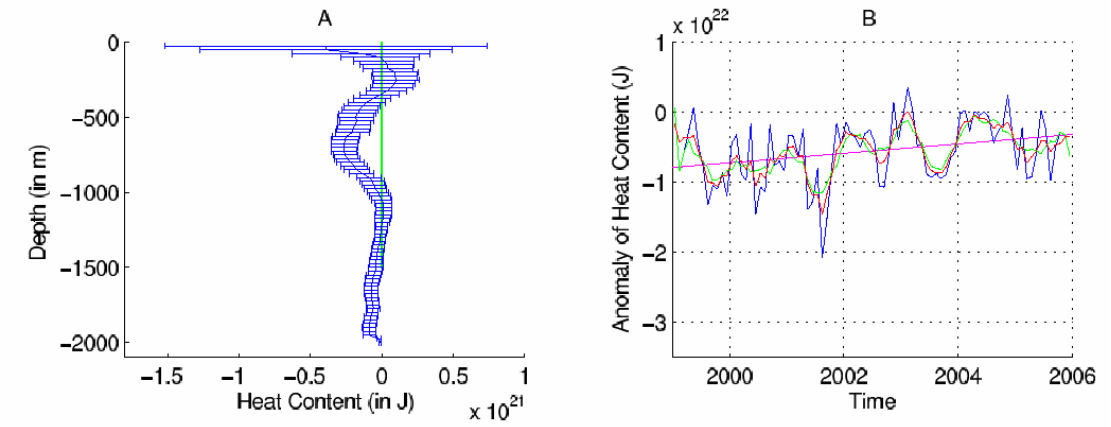

Figure D2. AHC of the North Atlantic, left vertical distribution of time averaged AHC where the horizontal bars represent 1 standard deviation; right AHC for the layer between 0 and 1,500 m, blue is AHC, green is moving averaged AHC, red a filtered AHC and magenta represents a linear regression.

Comparing the AHC for three layers: 100-500 m, 500-1,000 m and 1,000-1,500 m, we find negative values in all layers. The strongest anomaly corresponds to the layer 500-1,000 m. Analysis of the meridional averages for 10-degree strips (see figure D3) between 10° N and 70° N show a negative value in the southern and central sub-domains (SD) (10-50° N) and positive in the northern sub-domains. In the northern SD (50-70° N) positive values and a positive trend in the AHC is evident.

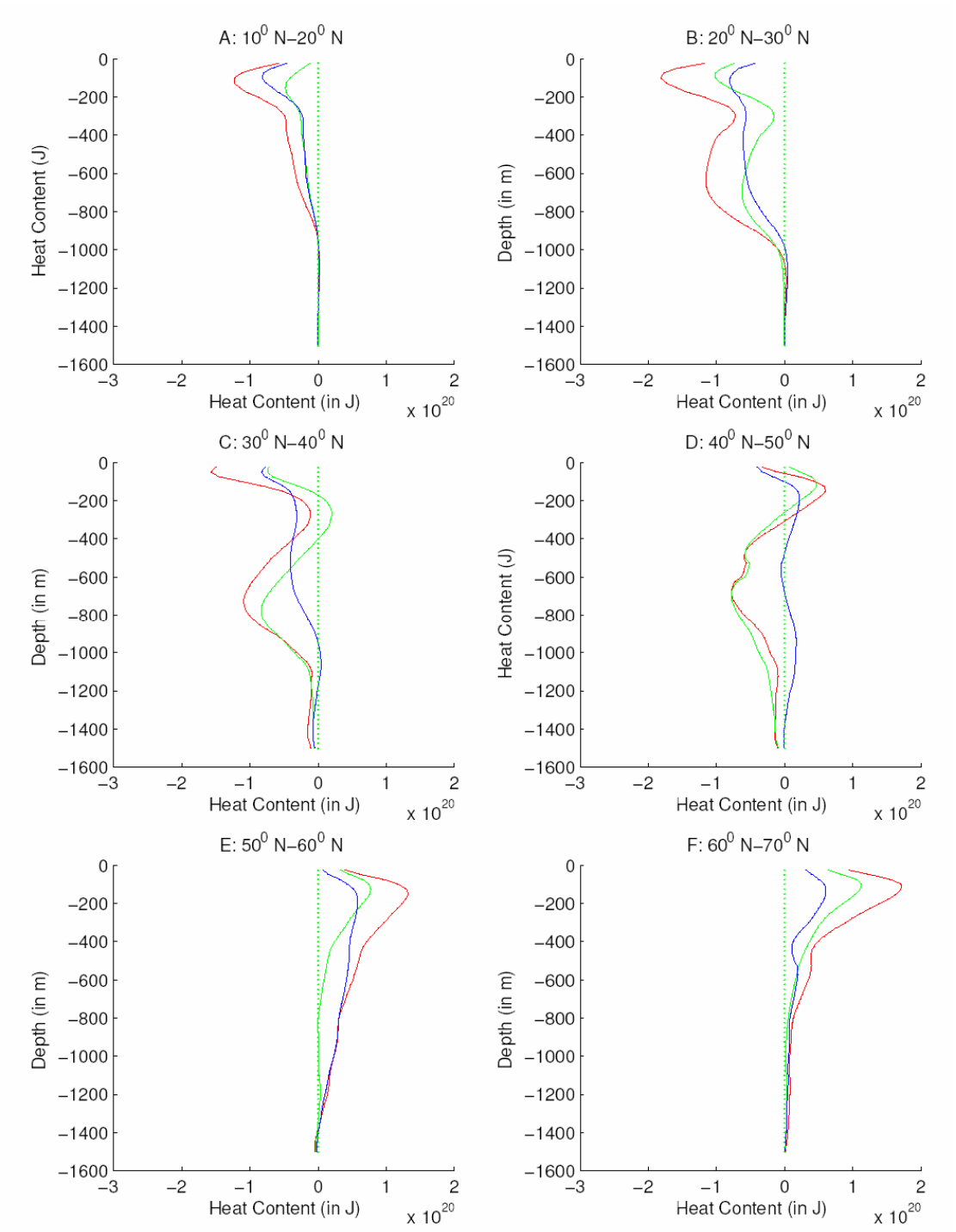

Figure D3. Vertical distribution of the time averaged Anomaly of Heat Content of the upper 1,500 m for the 10° bands: A: 10-20° N. B: 20-30° N. C: 30-40° N. D: 40-50° N. E: 50-60° N. F: 60-70° N. The red, green and blue represent the whole zonal band, the western and eastern parts, respectively.

The importance of Argo for physically-based ocean assimilation and the reconstruction of historical water mass variability – Keith Haines and Gregory Smith (ESSC, Univ. Reading)

Ocean assimilation is of great importance for both initialising ocean and coupled model predictions, as in seasonal forecasting for example, and for reanalysis of the oceans to determine currents and transports and to detect climatically important signals from the diverse historical ocean data that are available. The key aim of our research is to implement physically-based assimilation methods into a ¼ degree global ocean model to produce reanalyses over decadal timescales based on atmospheric reanalysis forcing and all available ocean hydrographic data, including Argo.

Our past experience with data assimilation has focused mainly on using physically-based algorithms (e.g. Cooper and Haines, 1996), which are essential for accurately representing water mass variations in a reanalysis. Latest work has demonstrated the benefit of combining Temperature (T) and Salinity (S) assimilation methods and of assimilating S(T) as the observable property (Haines et al., 2006), particularly for the new Argo data. Larger (and flow dependent) spatial and temporal decorrelation scales can be used for S(T), compared with S(z), allowing better recovery of water mass information. We also plan to generalise the S(T) algorithm to include the polar regions by assimilating spiciness on isopycnal surfaces. The implementation of this latter method is only possible due to Argo, as co-located temperature and salinity observations are required.

Data assimilation, when used as an analysis tool, allows large amounts of disparate data to be physically and dynamically interpolated to give a self-consistent solution to the ocean circulation. It also allows derived quantities such as transports and water transformation rates to be determined. We have focussed on developing assimilation methods that allow the water mass volumes to be correctly analysed from disparate hydrographic data. The new salinity assimilation method focussed on S(T) should be particularly useful when combined with Argo data to recover salinity and freshwater budget information. Moreover, this should allow a better assessment of the evidence for increasing salinity in tropical latitudes and increased freshening at polar latitudes, possibly associated with changes in hydrological cycle strength (Wong et al., 1999, Curry et al., 2003).

Recent studies have suggested that the Atlantic Meridional Overturning Circulation (MOC) may be undergoing a rapid slowdown (e.g. Bryden et al., 2005). This could have potentially dramatic effects on the oceanic component of the pole-ward heat transport thereby affecting the UK climate significantly. The deployment of an observing array at 26° N as part of the UK Rapid Climate Change programme will provide valuable information about the state of the MOC, but an understanding of how this circulation will respond to changes in surface fluxes and water mass properties is sorely lacking.

Historical temperature observations have provided a picture of heat content changes in the upper ocean. However, the paucity of salinity observations have hindered efforts at understanding the extent of freshwater variations. Moreover, it is the density variations associated with freshening in the deep water formation (DWF) regions that have the potential to affect the MOC, which could in turn significantly reduce the meridional heat transport. The Argo array has provided for the first time observations of density with sufficient spatial coverage that water mass anomalies in these critical DWF regions can be assessed. However, the continuance of Argo is required in order to understand how these water mass anomalies affect the MOC.

One of the principal difficulties in using ocean models to study the relationship between DWF and the MOC is the poorly constrained hydrological cycle. This difficulty can be at least partially overcome by using in situ observations of salinity from Argo together with a data assimilation system, thereby providing the ocean model with the correct water mass variations. Assimilating Argo data may thus allow us to recover changes in the MOC and Meridional Heat Transport (MHT) that were not simulated directly. This could provide a better understanding of the role of the western boundary in connecting high and low latitude changes in MOC. Moreover, water formation volumes generated by the assimilation can also be used to deduce errors in air-sea fluxes and transports in the model (Fox and Haines, 2003). Additionally, the extent of climatic signals noted directly from observational data (e.g. Dickson et al., 2003) can be determined within the simulated and assimilated reanalysis data sets. By verifying that the climate change signals detected directly from data can be found within the ocean reanalysis fields it will be possible to study the wider implications of these signatures and to put them in the context of coincident changes in MOC, MHT and water mass distributions.

Although a number of years of Argo data are required to contribute directly to assessing interannual and longer timescale variability, Argo will nonetheless be a critical resource in the short term to calibrate data assimilation systems. For example, one of the crucial parameters in any data assimilation system is the background error covariance matrix, for which an estimate of the covariance length scales is required. Sufficient data to calculate these length scales directly from observations is only now becoming available due to Argo. This is especially relevant for assimilation schemes, such as those discussed earlier, which require co-located temperature and salinity observations. The improved calibration of assimilation schemes provided by Argo will lead to both an increase in the accuracy of multi-decadal reanalyses, and a greater confidence in quantities derived from them, such as the MOC and MHT.

Annex E

The circulation in the subtropical South Indian Ocean derived from Argo floats – Klaus Getzlaff, Brian King, Elaine McDonagh and Harry Bryden (NOC, Southampton)

Recent studies have highlighted an increase in the gyre circulation across 32° S in the subtropical South Indian Ocean of up to 40% from analysis of shipboard observations made in 1987, 1995 and 2002. This study uses CTD profiles from Argo floats between 2001 and 2005 to compute the circulation in the subtropical South Indian Ocean as well as the impact of the variability of Sub-antarctic Mode Water and Antarctic Intermediate Water on the gyre transport.

An optimal interpolation scheme was used to map quality controlled CTD data obtained from Argo floats on to the 2002 cruise track and relative geostrophic transports are computed using a zero-velocity surface at 1,950 m. The interpolated density field from the float data represents the structure of the subtropical gyre interior well and the estimated strength of the gyre is 50 ± 9 Sv relative to and above 1,950 m (Fig. E1, red). This estimate of the gyre strength uses the maximum transport that can be attributed to the curve over the ocean interior, defined between 35° E and 110° E.

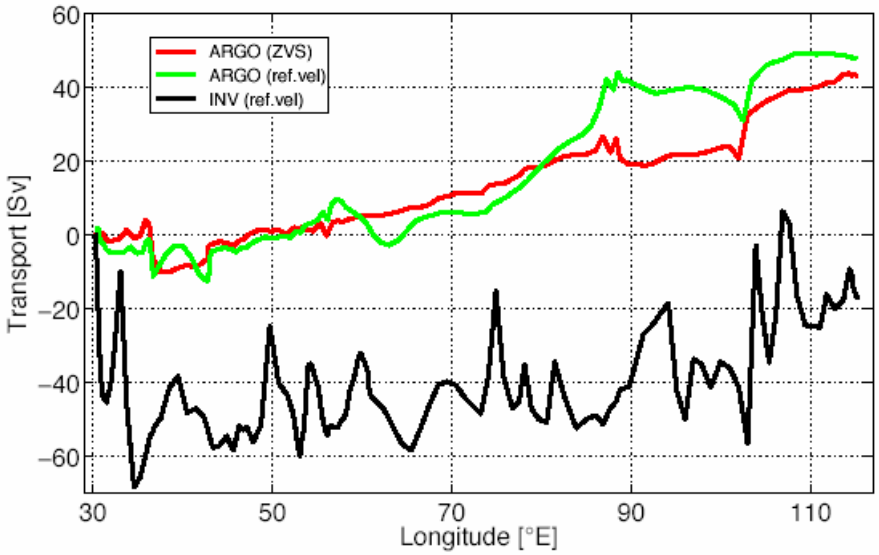

Figure E1: Cumulative transports calculated on the CD139 station grid using the interpolated Argo profiles either with a "zero-velocity-surface" at 1,950 m (red) or the reference velocities estimated from the float's subsurface drift, (see Fig. 2) used at 1,950 m depth (green). Additionally the inverse solution is shown (black) using the adjusted ADCP field as reference.

We have also computed a circulation scheme using reference velocities from the float's subsurface drift at 2,000 m (Fig. E2, green). Applying those reference velocities to the transport calculation increases the gyre strength to 61.6 Sv ± 11 (Fig. E1, green). Additional small scale features become visible like the increased northward transport east of Mozambique Plateau (35° E) and the increased southward transport west of Madagascar Ridge (45° E) and also the deep front east of 60° E is identifiable by an increased southward transport (Fig. E1 and E2, green). These small-scale structures are important for estimates of the overturning and they cannot be resolved by using a zero-velocity surface for the transport calculation (Fig. E1, red). Therefore the velocities from the float's sub-surface drift at parking

depth provide an important reference and additional parameter in the hydrographic data set.

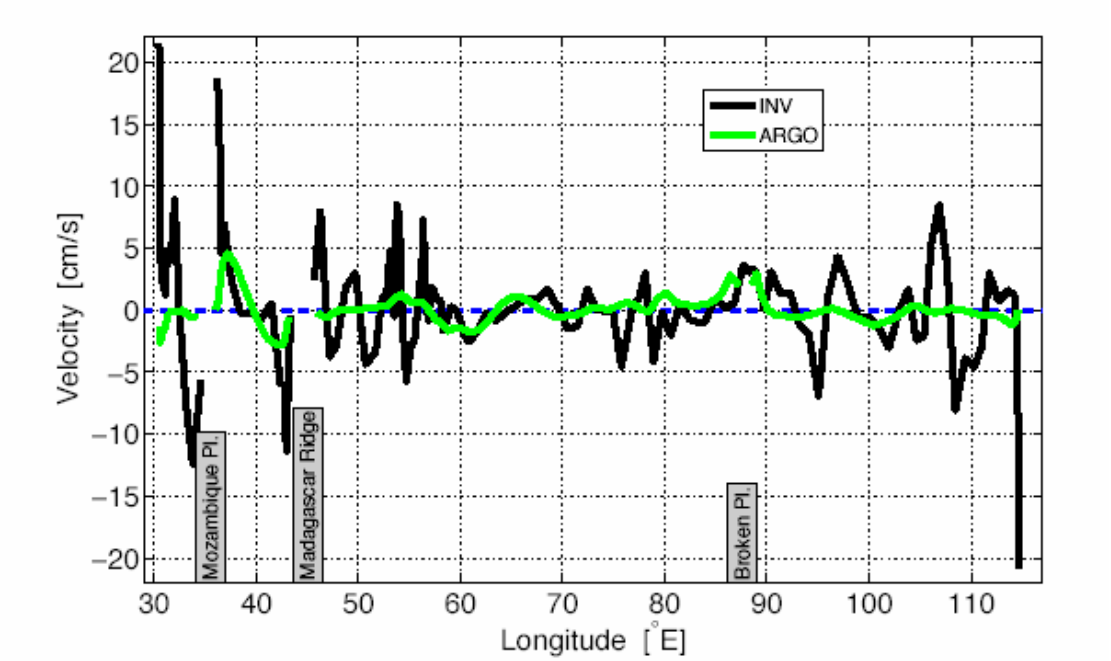

Figure E2: Reference velocities at 2,000 m across CD139 cruise track (Charles Darwin cruise in 2002). The optimally interpolated floats parking-depth velocities (green) are estimated from float's subsurface drift using the first and last positioning fix during each surface drift. The reference velocities from the inverse solution (black) use the high quality shipboard measurements collected during the cruise in 2002 together with oxygen and silicate distribution, LADCP velocity measurements and other constraints. "Zero-velocity" indicated by the dashed blue line.

The result is compared to the unfiltered cumulative transport using the solution from an inverse calculation initialised with the adjusted ADCP field with an estimated gyre strength of 74.8 Sv (Fig. E1 and E2, black). The differences in the gyre transport are due to the time period covered by both data sets (4 years from the Argo floats and 2 months from the hydrographic cruise data) as well as due to low float data coverage in some areas.

Nevertheless, the almost exponential increase in float data availability over the last years and in the future, does provide the opportunity to analyse the interannual variability in this region in more detail, which will be the next step to do.

Annex F

Float technology problems that have been addressed

Motor backspin. The backspin problem which was found in the earlier Apex floats (prior to 2002) was due to the external hydraulic pressure on the oil bladder at depth > 1,500 m. The pressure was sufficiently high to cause the piston motor to spin backwards thus generating a voltage (typically >30V) damaging the voltage regulator and electronics. In this instance, the unit fails to resurface. The backspin problem was subsequently fixed by Webb Research in late August 2002, all Apex floats with serial numbers 698 or higher have the problem corrected and so cannot fail in this mode. This problem affected a number of UK floats deployed in 2001 (6 to 8 floats) and 2002 (11 or 12 floats).

Pressure transducer. All Apex floats are fitted with Sea-Bird electronics SBE41 CTD unit. The earlier pressure transducers (2002-2003) were prone to damage due to electrostatic discharge during handling and deployment. A faulty pressure transducer produces erratic pressure measurements (generally easily identifiable) and/or out of range pressures (>3,000 dBar), although the floats often continue to cycle (although data reported are invalid). However, because the Apex float requires pressure data to conduct a successful profile, the problem ultimately prohibits the instrument from profiling. A specific problem was identified in August 2003 and subsequently corrected. A number of our susceptible floats were recalled, hence the relatively low number of UK Argo floats deployed that year. However, occasional pressure transducer failures can still occur. Pressure transducer problems affected 1 float in 2001, 15 floats in 2003 and 1 in 2004.

Battery deficit/battery flu. This problem is now the major cause of premature float demise with around a third of all Apex floats suffering from this problem. It occurs where the floats are fitted with alkaline batteries. The floats suffer from a rapid decline in battery voltage which may be due to failure of one or more battery cells, this can often be seen from the engineering data, as shown below.

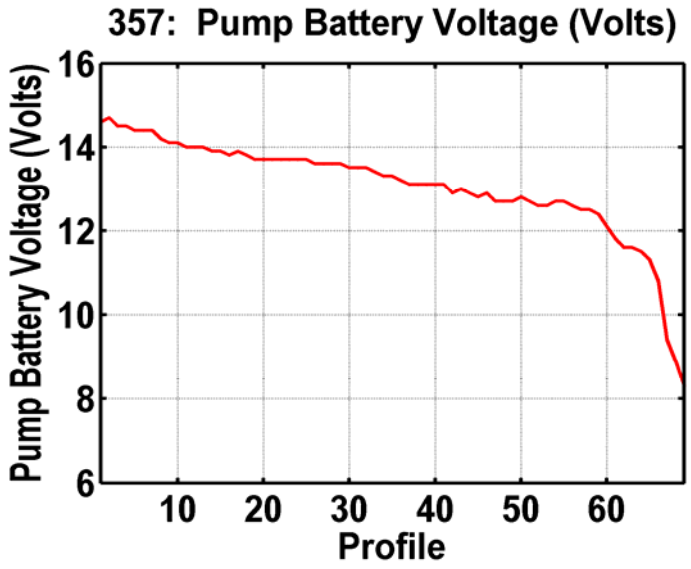

Figure G.1. Battery voltage plot for float 1900085, showing a rapid voltage decline after around 60 cycles.

Attempts have been made to mitigate the effect by fitting each cell with a bypass diode (impolemented in February 2004) so that when an individual cell fails it does not take out the entire pack, thus prolonging the floats lifetime (but which is still reduced by cell failure).

FSI salinity sensor problems. In addition our MARTEC Provor floats were all fitted with FSI salinity sensors. Our early Provors suffered from a problem in which the salinity exhibited a major shift. One explanation offered for this was movement of the flotation collar so it affected the (inductance) salinity sensor. Other early Provors suffered problems due to contamination by the anti-fouling coating and in 2003 15 of our Provors were recalled to have the coating removed. These were deployed in late 2004 / early 2005 and have shown better reliability. Following the problems that arose with the FSI sensors Provor floats are now only supplied with Sea-Bird sensors.